X-Sieve: CMU Sieve 2.2
From: Acaj1@aol.com
Date: Fri, 5 Aug 2005 17:26:19 EDT
Subject: Reoprt by Prof. Quintiere WTC Collapse
To: info@nistreview.org
CC: ncstac@nist.gov, sallyr@skyscrapersafety.org, wtc@nist.gov
X-Mailer: 9.0 Security Edition for Windows sub 5200
X-Spam-Flag: NO
X-NIST-MailScanner-Information: Please contact the ISP for more information
X-MailScanner:
X-MailScanner-From: acaj1@aol.com

Eric,

Attached for posting is a report by Professor James Quientiere with some suggestions by myself.

Thanks.

Arthur Scheuerman,
Ret. B.C. FDNY

NIST WTC 7-05 Suggestions.pdf

Comments on NIST NCSTAR 1 Draft

July 27, 2005

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With suggested changes in red to NIST report by Arthur Scheuerman

General Comments

These comments pertain to the NIST summary chapter of the NCSTAR 1 Draft report, and are based on statements also from the June 2005 progress report. My comments will be annotated (Appendix A) to indicate their source and to provide additional information.

My comments address the fire analysis, the heating of the steel and issues pertaining to such. In summary, I list the issues and concerns that I have with the NIST presentation and findings:

1. I do not believe that NIST has presented a convincing argument for their collapse hypotheses for WTC 1 and 2. NIST had repeatedly stated that they would list all likely collapse scenarios in terms of their probabilities based on uncertainties in the analyses. That seems to have been abandoned in the final report. Their collapse hypothesis is based on damage done by the aircraft impacts, particularly in removing insulation from the core columns is key, together with brief local fire heating of above 1000 oC for about 15 minutes. NIST has not made a sufficient case for the removal of the steel insulation, and the fire analysis is based on a light fuel

load that is shown to be in error. I suggest an alternative hypothesis based on longer fire duration, and on the insulation staying primarily in place.

2. NIST claims that if the insulation had stayed in place, the computed fire was not able to cause building collapse. Therefore, they conclude that the insulation applied in design was adequate: "The WTC towers would likely not have collapsed under the combined effects of aircraft impact damage and the extensive, multifloor fires if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact." [p172] I have not seen sufficient evidence to indicate that the insulation was removed, nor that the insulation applied, had it remained in place, was adequate.

3. NIST was not able to document the WTC design process with respect to the selection of the steel insulation or its basis: "NIST was not able to find any evidence that there was a technical basis to relate SFRM thickness to a fire resistance rating, nor was there sufficient prior experience to establish such thickness requirements by analogy." [p 55] the lack of findings is a tragedy of this investigation as it goes to the core of fire protection design and its dependence on regulations. If we do not know how the process worked for these buildings, how do we know it is being done satisfactorily now.

4. The report represents more of a scientific analysis rather than an investigation to find all of the relevant facts. NIST held no hearings to ascertain testimony, used no subpoenas, and enlisted no investigative team to gather information. NIST was very late in acquiring witness accounts due to the federal government bureaucracy requirements on public surveys. Steel remnants were collected as they were available, and reports from the PA or others involved were taken as fact without corroboration. An example is the acceptance of insulation applied to the trusses in renovation to the north tower, WTC1, impact area as 2.5 inches compared to the

specification of 1.5 inches over the original 0.5 inches. This is an incredible difference, realizing that they reported up to 4 inches applied to a 1- inch diameter rod. ("The Port Authority provided NIST with the records of measurements of SFRM thickness on upgraded floors in both towers. The average thickness and standard deviation on the main trusses was 2.5 in. ± 0.6 in. NIST analysis of several Port Authority photographs from the 1990s of the upgraded 31 st floor of WTC 1 indicated an average thickness and standard deviation on the main trusses of 1.7 in. ± 0.4 in.") [p 70] Had more steel been examined from the fire floors, NIST may have been able to establish proof for its hypothesis that key core columns were denuded of insulation and therefore significantly heated to cause their reduction in strength. NIST found no evidence to corroborate that finding. "None of the recovered steel samples showed evidence of exposure to temperatures above 600 C for as long as 15 min. This was based on NIST annealing studies that established the set of time and temperature conditions necessary to alter the steel microstructure. These results provide some confirmation of the thermal modeling of the structures, since none of the samples were from zones where such heating was predicted." [p 176] Had NIST recovered steel from the areas where steel was predicted to have been heated, could have given them key evidence to support their claim. As the steel was expeditiously sold to Asia, before the fire floor steel could be identified from its markings and saved, was a significantly blunder in the investigation. Since NIST has jurisdiction over future investigations, a protocol for protecting evidence and securing the site must be established. Moreover, the rationale for the speedy elimination of the steel in this incident, NIST fails to document. Spoliation of fire scene evidence can border on a crime.

5. The NIST report is difficult to read due to its length and tedious style. It does not clearly show cause and effect. Standard analyses of fires attempt to give a time line. While the actual

timeline is clearly known in this case, the predicted timeline and its cause and effect listing is not presented. There are vague references that the predicted fire looked right. Dr. Sunder indicated that a timeline was not predicted, as difficulties exist with the nonlinear creep structural model. Only a mechanistic analysis was presented [NFPA meeting at NIST, July 12, 2005]. The report needs to clearly indicate the scientific reasons for the NIST description of the collapse scenarios and tie them to the results of their computations and assumptions. This needs to be done with footnoted annotations so a reader can find the details. This 10,000- page report will only serve as a smoke screen unless it is fully documented for easy reference.

6. NIST has never acknowledged of answered comments in the past, so it is doubtful that these comments will have any impact. I urge them to be more responsive. I am attaching my unanswered November 22, 2004 comments for background. (Appendix B)

Specific comments:

1. Collapse Hypothesis

Structural Failure

NIST contends that the collapse is due the floors pulling in the external columns that in turn lose stability [p 171,2]. This occurs on the south of WTC 1 and the east of WTC 2. They say WTC 2 collapses earlier because it received more damage from the aircraft.

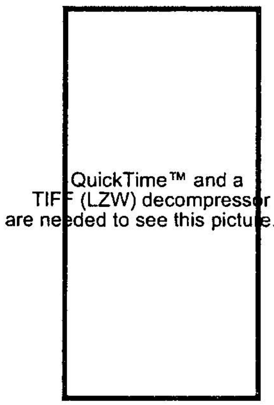
I find an alternative hypothesis that can be supported by relatively simple computations on the heating of the steel trusses with their specified insulations in place [Quintiere et al, Fire Safety J. 2002, and Quintiere, Interflam 2004]. This analysis does not include the heating of the core columns, as they would never get hot enough to fail if their insulation remained intact. Table 1 summarizes the results, and shows computations for a fire of 800 °C, and indicates the time for the steel to reach 600 °C where it falls to 20 % of its original strength. The truss at this temperature would fail due to the deflection pulling in the external columns as indicated by Usmani [FSJ 2003], and by NIST [June 2004 Progress report, Vol 1, p 81, 120] by either this column buckling or by failure of the connections. Buckling can occur at steel temperatures as low as 400 °C while the seat failure occurs at 650 °C.

It is noted that the predicted times to reach the critical failure temperature of the truss steel of 55 -73 minutes for WTC 2 and 111 minutes for WTC 1 in Table 1 is consistent with the building collapse times of 56 and 102 minutes, respectively. These predicted heating times are also consistent with the NIST measured heating times (to 66 to 86 minutes, although the reduced scale 17 ft span tests compromised heat transfer) in the UL furnace tests at fire temperatures comparable to 800 °C shown in Table 2 taken from NIST. Indeed, the UL time to reach 1100 °F (593 °C) for the 35 ft span ranges from 66 to t6 minutes which is consistent with 73 minutes in Table 1 and an extrapolated time of 50 minutes for the UL temperature conditions. (See Figure 1.)

Table 1. Time for steel elements to reach 600 °C in an 800 °C fire (Interflam 2004).

Element	Insulation Thickness mm	Time to Reach 600 °C with insulation, min.	Time to Reach 600 °C with no insulation, min	E119 Rating Requirement min.
27.7 mm rod, 54 kg/m^2 WTC 2	12.7	55	8	120
N WTC 2	19.1	73	8	120
N WTC 1	38.1	111	8	120
14WF43, 43 kg/m^2 core	44.5	213	6	180
55.8 cm box column, 7.6 cm thick, 513 kg/m ^{2} core	28.6	1640	75	180

Table 2. UL test results form NIST



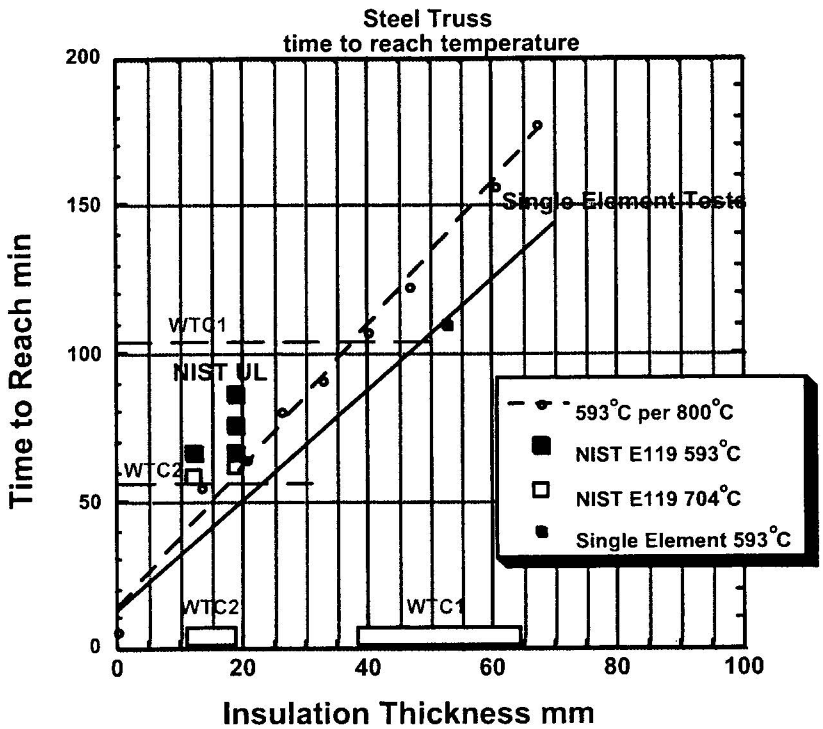


Figure 1. UL and Isolatek results.

Consequently, if the truss elements with specified insulation levels of ½- ¾ in. for WTC 2 and 1 ½ in. for WTC 1 can be heated to about 600 °C in an 800 °C fire at computed times of 55-73 minutes and 111 minutes, respectively, and NIST and others determined that the truss would cause either column buckling or connection failure at 600 °C or below, then this mode of collapse cannot be discounted. This is especially compelling since the collapse times are consistent at 56 and 102 minutes. Moreover, it is commonly known that floor sections were collapsing up to 20 minutes before the full collapse of each of the buildings. NIST has not addressed those early failures.

Fire Simulation

The results of the NIST fire predictions are based on a fuel loading of 4-5 psf. These levels are based on data from the impacted floors of Marsh & McLennan in WTC 1. NIST says this has "high" accuracy [p 119]. They find for WTC 1 that a given floor did not have uniform temperatures. "At any given location, the duration of temperatures near 1,000 °C was about 15 min to 20 min." [p 127] Upper layer temperatures are shown in Figure 2 for WTC 1 97th floor [NIST]. Temperatures generally exceeded 600°C for about 30 minutes, and for about 60 minutes in the core. In contrast, a scale model test conducted at the University of Maryland, representative of the 96th floor with a simulated fuel load of 11.5 psf, shown in Figure 3 indicates temperatures are generally over 6000C(typo?, 600C) for 100 minutes, by(typo?) are much cooler in the core. These results are distinctly different from the NIST simulation. One may be dubious of scale modeling, but it is a tried and true technique.

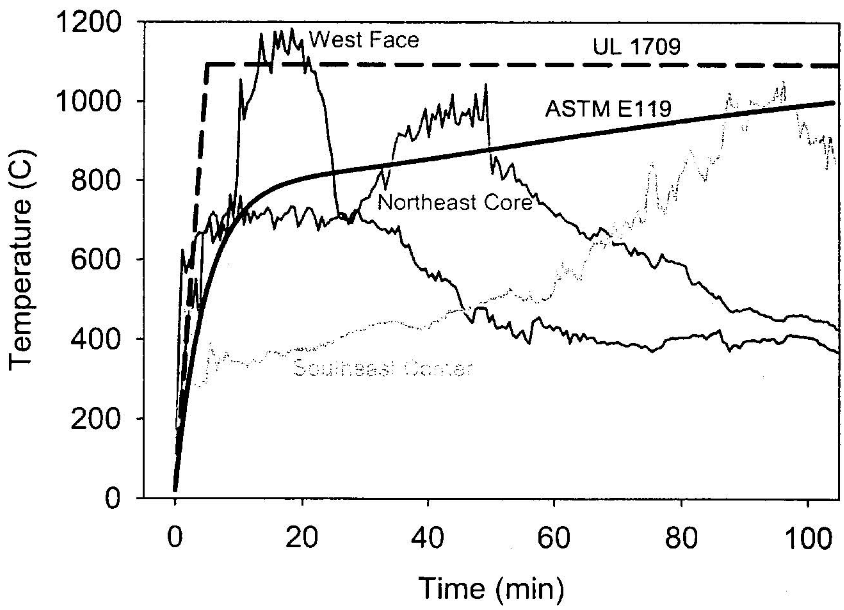


Figure 2. Predicted upper layer temperatures at various locations on the 97th Floor.

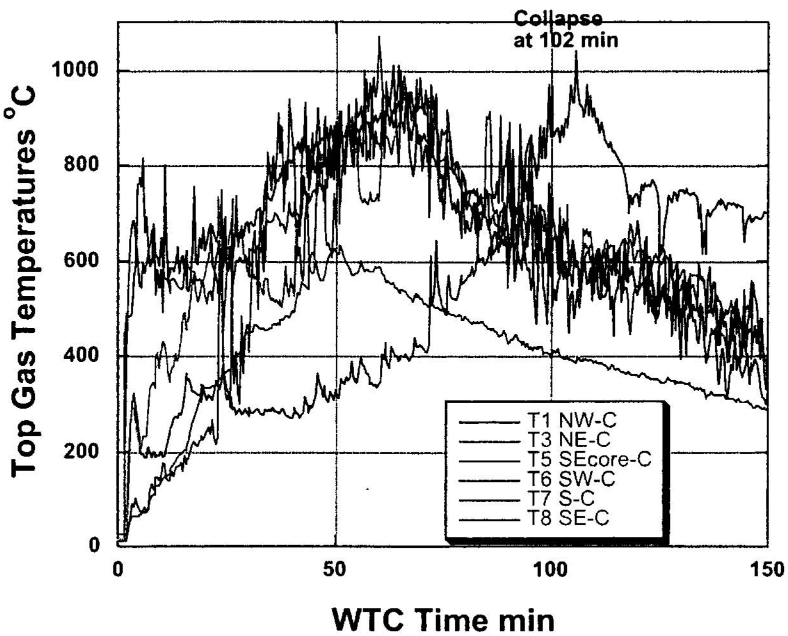


Figure 3. Temperatures in a scale model of WTC 1 96th floor

The heavier fuel load in the scale model was based on traditional office loadings and on anecdotal interviews of people familiar with the floors. Subsequently, we conducted a fuel load survey of the 96th floor based on architectural plans obtained from the furniture installer. This led to a conclusion that a loading of 10 psf or greater was the case. Appendix C contains the details in a report. Figure 4 shows a section of the architectural plans used for the 96th floor. A handwritten notation indicates a section of common files that ringed the core of the office space. There were 170 of these 4-drawer lateral files. NIST completely ignored this fuel load (and others) in their assessment. We assigned 100 lbs of paper per draw (a sub-capacity level) giving 68,000 lbs for this contribution. In addition, there were other common files and a storage room that gave a grand total of 95,400 lbs not included by NIST. In the survey conducted by Kate Stewart, estimates of paper and personal items were included in the workstation loads based on typical office conditions. Our total floor combustible loading was estimated at 302,062 lbs compared to 134,640 lbs determined by NIST. Taken over the office floor space area (31,013 ft^2), this computes to 9.7 psf and 4.3 psf for NIST. Our paper extimat per file draw is well below

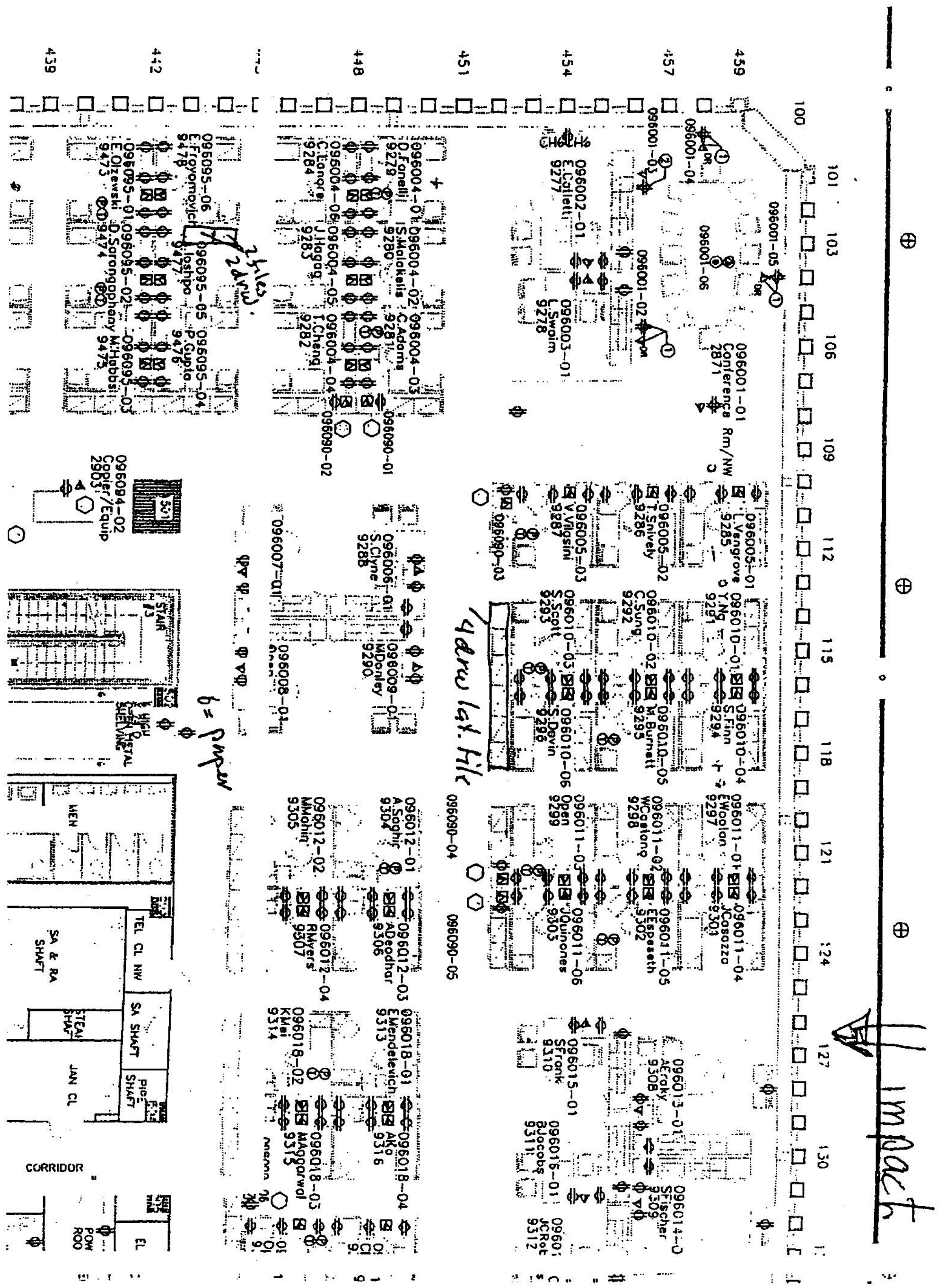


Figure 4. Section of furniture layout WTC 1 96th floor

capacity, so the loading we determine is likely too low. Indeed, it was told to us that Marsh was a "paper hog" and "kept everything". Paper fuel in closed files is de-rated in fire design considerations, but the aircraft impact could have opened the file draws.

It is generally expected that fully developed fires achieve nearly uniform temperature of over 800°C, and are expect to persist for hours. Hence, we have the standard rating of structures at 2 to 3 hours of endurance. Had NIST used higher fuel loadings, they would have had longer hot fire conditions and this would impact their input into the structural modeling. The discrepancy in the fuel load raises some questions. Moreover, the large differences in the fuel loading found by us and NIST on the Marsh floors raises more questions. Incidently, our independent check of the workstations exclusively counted by NIST gave us a combustible load of 133,694 lbs compared to their count of 134,640 lbs. In addition, while NIST claims high accuracy for the loading in WTC 1, they do not for WTC 2. Moreover, it appears that the fire simulation in WTC 2 is only about half the size of WTC 1. More needs to clarified here.

2. Insulation Lost on Impact

NIST has not presented clear and sufficient evidence that the aircraft impacts caused the elimination of insulation, especially from the core columns. According to NIST [Sunder, July 12, 2005 NFPA committee meeting], the planes disintegrated on impacting the exterior columns. This debris and its momentum is alleged to have removed the insulation. Heavy item, such as an engine or landing gear, could cause structural damage to a column in the core: "If the engine missed the floor slab, the majority of the engine core remained intact and had enough residual momentum to sever a core column upon direct impact. " [p 105] This suggest that hitting a floor slab, which is very likely due to the diameter of the engine, then less damage would be done. Moreover, the accuracy of the impact calculation is not high as other compute different damage results. Specifically on the insulation loss, NIST says it could be shook off due to vibrations, or eroded off due to pulverized debris impact. On the former NIST concludes: "The analyses were not sufficient to establish justifiable, general criteria for a coherent pattern of vibration-induced dislodging." [p 117] ON the erosion, NIST did static tests on the insulation adhesive strenth, but never coupled these results to a computational model. Instead, "NIST assumed that the debris impact dislodged insulation if the debris force was strong enough to break a gypsum board partition immediately in front of the structural component. Experiments at NIST confirmed that an array of 0.3 in. diameter pellets traveling at 350 mph stripped the insulation from steel bars like those used in the WTC trusses." [p 117] These pellet tests need more amplification, as they are the only test simulation of the erosion effect. Moreover, the test speed of 350 mph is not consistent with the average speed of debris traversing the buildings. The debris took about 0.7 s [sunder, July 12, 2005] to exit, giving an average speed of 205 ft/0.7s or 200 mph. As momentum depends on the square of the velocity, NIST has overestimated the momentum in these pellet tests by a factor of 3.

It is crucial to the NIST collapse hypothesis that the insulation is removed on impact. It begs more support.

3. WTC Fire Resistance Design

From the outset of its construction, fire safety was a concern for the WTC. From the records, clearly cost, time and safety were involved. For NIST not to have probed these facets, and to assess, in the least, the disparate range of insulation thickness assigned to the floor assembly truss system a dereliction of the intent of this investigation. NIST cites historical facts [p 69 +], but not the underlying rationale for decisions. Although an extensive civil suit on the insulation deficiencies occurred in the 1990's, NIST appears to have not examined those records.

How can on justify a specification of ½ in., a change to 1 ½ in. in the 90's, an ICBØ recommendation of 2 in. [p 192], and an actual upgrade to 2.5 +/- 0.6 in. on the impact floors of the WTC 1? The extensive over-application up to 3 in. on a round 1 in. diameter bar-joist is difficult to accept based solely on a report from the PA when photographic evidence for other upgraded floors shows only 1.7 +/- 0.4 in. according to NIST [p 71].

Whether this insulation on the truss was key as I believe, or not, is not the issue here. The process of fire resistance regulations and their interpretation is the issue. This needs to be scrutinized. It should have been at the heart of the investigation, and that is why NIST has proceeded as a scientific body rather than an investigative agent. Civil lawyers would have pushed this, whereas the Commerce lawyers seemed more concerned to restrict the scientists, and block information from the public.

4. Lack of In Depth Investigation

The NIST report reads like a scientific enterprise using computer simulations that have never been used (or validated) in this way before. [119] Other government agencies that have investigative authority operate differently. The NTSB has time scene presence, press briefings, and formal hearings with testimony. The ATF has a National Response Team that is on the scene within hours of the event. They secure the scene, question witnesses, and gather evidence. NIST has operated in near secrecy, has had a low public profile, and has gathered facts as in a library search. Although they have held public forums, these have been very controlled, under publicized, and dominated by NIST. They have not appeared to have aggressively, or with corroboration in mind, pursued evidence. The Commerce lawyers could have helped here. With the amount of funding that they received they could have conducted a full-scale test of a floor. They could have given more support to their purely mathematically modeling results. As scientists are sometime stereotyped as being out of touch with reality, NIST cannot afford that stigma as an investigative body as NCSTAR.

5. On the Recommendations

Thirty recommendations are listed. They all are general and imply more research is needed. One cannot fault NIST fro trying to expand its research base, as they have not been properly funded in the fire and building areas since the 1970's. The fire funding with NSF and industry support ran as high as $ 10 million in the mid- 70's. Its comparable level in today's dollars is much lower. But the funding issues should not cloud the work of the NCSTAR. Yet the NCSTAR is only authorized to proceed and funding for its continuation is doubtful. So perhaps funding is the real issue.

The recommendation areas cover:

1. Increased structural integrity, including methods for preventing conditions that could result in progressive collapse (when a building or a significant portion of a building collapses due to disproportionate spread of an initial local failure), standardizing the estimation of wind loads that frequently govern the design of tall buildings, and enhancing the stability of tall buildings.
2. Enhanced fire resistance of structures, including the technical basis for determining construction classification and fire resistance ratings, improvements to the technical basis for standard fire resistance testing methods, adoption of the "structural frame" approach to fire resistance ratings, and in-service performance requirements and conformance assessment criteria for spray-applied fire resistive materials.
3. New methods for designing structures to resist fires, including the objective of burnout without collapse, the development of performance-based methods as an alternative to current prescriptive design methods, the development and evaluation of new fire resistive coating materials and technologies, evaluation of the fire performance of conventional and high performance structural materials, and elimination of technical and standards barriers to the introduction of new materials and technologies.
4. Improved active fire protection, including the design, performance, reliability, and redundancy of sprinklers, standpipes/hoses, fire alarms, and smoke management systems.
5. Improved building evacuation, including system designs that facilitate safe and rapid egress, methods for ensuring clear and timely emergency communications to occupants, better occupant preparedness for evacuation during emergencies, and incorporation of appropriate egress technologies.
6. Improved emergency response, including better access to the buildings and better operations, emergency communications, and command and control in large-scale emergencies.
7. Improved procedures and practices, including encouraging (legislating?) code compliance by nongovernmental and quasi-governmental entities, adoption and application of egress requirements in available code provisions for existing buildings, and retention and availability of building documents over the life of a building.
8. Education and training programs for fire protection engineers, structural engineers, and architects.

I generally support NIST in all of these areas, as they are important areas to pursue for research. Recommendation that can lead to immediate code changes need to go more slowly, as they require consensus and checks and balances. NIST as part of its name suggests can play an important role in "Standards" for fire safety, but they must be enabled to do that successfully. The fire and building programs at NIST have atrophied, and must be brought back to full competence. These and other programs at NIST must rely on outside funding to support their staffs. That effort, in particular, takes away form the fire program, as industry does not wish to fund safety regulations. For other programs in NIST where standards benefit industry and grease the market place, those programs find fertile support in industry. Fire safety is different, and the congress needs to appreciate that, and direct its funding accordingly.

I would like to offer some more specific comments to the NIST recommendations # 29 and 30 that pertain to education. They advocate "continuing education curricula" for structural and fire engineers and architects on modern principles and on the use of computational methods. While this is good, it is not enough; and it could produce people who think they have expertise, but do not. The education in fire protection engineering is sorely lacking in the US. Only about 50 engineers are produced a year at institutions granting a recognized engineering degree (U of MD, WPI) and technology degrees (OSU, U of Akron, etc.). The US likely needs 500 engineers a year. While a careful study of the need has not been done, the training received in continuing education courses currently indicates the lack of fire protection engineer in the field of fire investigation and in the protection of nuclear plants as stark examples. In addition, the population that makes up the regulators and participate in the code and standards making process generally lack degrees. The estimate I cite comes from the fact the University of Lund program in Sweden place all of their graduates at a rate of 2 in million of population per year in the private sector and 2 more in the fire service profession. This gives a benchmark of 2 to 4 per million of population. If the fire service in the US began to hire fire protection engineers, the estimate for the US would be 1000 per year.

The Congress needs to bring the education level of fire protection engineering up to a level that fill the infrastructure needs for the country. This can be fulfilled with NSF providing funds to this field. The Congress needs to further recognize that NIST is under funded in these areas, and the country needs a better way of getting the proper technical input into the regulatory process for fire safety. It cannot be dependent on voluntary efforts and special interest actions. After the tragedy of 9/11, a better process of fire safety needs to be created. Unfortunately, the NIST NCSTAR draft report does not dramatically demonstrate the deficiencies in the fire process for the design and collapse of the WTC buildings.

Appendix A: NIST NCSTAR 1 Draft Source Material

Collapse Cause

Why the collapse, p171,2

Objective 1: Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft. • The two aircraft hit the towers at high speed and did considerable damage to principal structural components: core columns, perimeter columns, and floors. However, the towers withstood the impacts and would have remained standing were it not for the dislodged insulation and the subsequent multifloor fires. The robustness of the perimeter frame-tube system and the large size of the buildings helped the towers withstand the impact. The structural system redistributed loads without collapsing in places of aircraft impact, avoiding larger scale damage upon impact. The hat truss, which was intended to support a television antenna atop each tower, prevented earlier collapse of the building core. In each tower, a different combination of impact damage and heat-weakened structural components contributed to the abrupt structural collapse. • In WTC 1, the fires weakened the core columns and caused the floors on the south side of the building to sag. (this sentence should read "The fires caused the floors on the South side of the building to sag and weakened the core columns.") The floors pulled the heated south perimeter columns inward, reducing their capacity to support the building above. Their neighboring columns quickly became overloaded as the south wall buckled. The top section of the building tilted to the south and began its descent. The time from aircraft impact to collapse initiation was largely determined by how long it took for the fires to weaken the building core and to reach the south side of the building and weaken the perimeter columns and floors. (This sentence should read; "The time from aircraft impact to collapse initiation was largely determined by haw long it took for the fires to weaken the long span floors on the south side of the building. In WTC 1 the perimeter wall and the core were heavily damaged on the North side and if it were not for the South side floors sagging and failing, destabilizing the South perimeter wall and possibly the core, the building would have tilted to the North before collapsing.") • In WTC 2, the core was damaged severely at the southeast corner and was restrained by the east and south walls via the hat truss and the floors. The steady burning fires on the east side of the building caused the floors there to sag. The floors pulled the heated east perimeter columns inward, reducing their capacity to support the building above. Their neighboring columns quickly became overloaded as the east wall buckled. The top section of the building tilted to the east and to the south and began its descent. The time from aircraft impact to collapse initiation was largely determined by the time for the fires to weaken the perimeter columns and floor assemblies (change to; "to waken the floor assemblies and possibly the perimeter columns") on the east and south (eliminate "east and") side of the building. WTC 2 collapsed more quickly than WTC 1 because there were early and persistent fires on the east side of the building, where the fireproofing was thinner and had not been upgraded and aircraft may have extensively dislodged insulation from the structural steel. Since the core columns on the lower floors in Tower 2 were much more robust than in Tower 1, it was unlikely there was more aircraft damage to the building core. • It is unknown whether the WTC towers would likely have collapsed under the combined effects of aircraft impact damage and the extensive, multifloor fires if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact. A full scale test of the 60 foot long span flooring assembly is needed to clarify thermal stability problems.

On WTC 1: p xliii-xliv

The two aircraft hit the towers at high speed and did considerable damage to principal structural components: core columns, floors, and perimeter columns. However, the towers withstood the impacts and would have remained standing were it not for the (add "deficient", "inadequate" or) dislodged insulation (fireproofing) and the subsequent multifloor fires.

The time from aircraft impact to collapse initiation was largely determined by how long it took for the fires to weaken the building core and to reach the south side of the building and weaken the perimeter columns and floors. (change to "... largely determined by how long it took to weaken the floors which sagged and possibly detached destabilizing the heat weakened perimeter columns and building core."

On WTC 2

n WTC 2, the core was damaged severely at the southeast corner and was restrained by the east and south walls via the hat truss and the floors. The steady burning fires on the east side of the building caused the floors there to sag. The floors pulled the heated east perimeter columns inward, reducing their capacity to support the building above. Their neighboring columns quickly became overloaded as columns on the east wall buckled. The top section of the building tilted to the east and to the south and began its descent. The time from aircraft impact to collapse initiation was largely determined by the time for the fires to weaken the floor assemblies and perimeter columns and on the east and the south sides of the building. WTC 2 collapsed more quickly than WTC 1 because there were early and persistent fires on the east side of the building, where there was less insulation on the structural steel. Whether there was more aircraft damage to the building core and aircraft had extensively dislodged the insulation is still questionable.

Also an analysis of the stability of the towers, assuming no damage to the core, gives the number of floors that need to be removed to cause global failure (June 2004, Vol. 1, p.81):

> The following presents some preliminary findings obtained from the preliminary stability analyses under service live loads and subject to the assumptions and the limitations of these models (see Appendix D): Linear stability analysis was used to examine the stability of the undamaged WTC 1 under service loads through increased un-braced column lengths (floor removal). The tower was stable when two complete floors including the core floors were removed. Two core columns buckled when three floors were removed, but the tower maintained its overall stability. The tower also maintained its stability when four columns buckled with four floors removed. The analysis suggested that global instability of the tower occurred when five floors were removed from the model. Assuming that all columns at the region of the removed floors reached a temperature of 600 °C (reduced modulus of elasticity), the analysis indicates that removal of four floors would induce global instability.

1. <u>Single truss analysis</u>: A model of a single truss and its connection shows that the truss fails at the interior column seat connection, and 'walks off' the seat. This occurs at 650 C. The web diagonals begin to buckle at 340 C, and the exterior columns bow inward at 560 C as the truss to acted as a catenary. (June 2004, Vol. 1 p. 120).

On steel inspected p 88,89

Examination of photographs showed that 16 of the exterior panels recovered from WTC 1 were exposed to fire prior to the building collapse. None of the nine recovered panels from within the fire floors of WTC 2 were directly exposed to fire. NIST used two methods to estimate the maximum temperatures that the steel members had reached: • Observations of paint cracking due to thermal expansion. Of the more than 170 areas examined on 16 perimeter column panels, only three columns had evidence that the steel reached temperatures above 250 °C: east face, floor 98, inner web; east face, floor 92, inner web; and north face, floor 98, floor truss connector. Only two core column specimens had sufficient paint remaining to make such an analysis, and their temperatures did not reach 250 °C. NIST did not generalize these results, since the examined columns represented only 3 percent of the perimeter columns and 1 percent of the core columns from the fire floors. • Observations of the microstructure of the steel. High temperature excursions, such as due to a fire, can alter the basic structure of the steel and its mechanical properties. Using metallographic analysis, NIST determined that there was no evidence that any of the samples had reached temperatures above 600 oC. These results were for a very small fraction of the steel in the impact and fire zones. Nonetheless, these analyses indicated some zones within WTC 1 where the computer simulations should not, and did not, predict highly elevated steel temperatures. 6.5

On the steel p 176

None of the recovered steel samples showed evidence of exposure to temperatures above 600 oC for as long as 15 min. This was based on NIST annealing studies that established the set of time and temperature conditions necessary to alter the steel microstructure. These results provide some confirmation of the thermal modeling of the structures, since none of the samples were from zones where such heating was predicted.

On single truss analysis p 96

Single composite truss and concrete slab section. A floor section was modeled to investigate failure modes and sequences of failures under combined gravity and thermal loads. The floor section was heated to 700 °C (300 °C at the top surface of the slab) over a period of 30 min. Initially the thermal expansion of the floor pushed the columns outward, but with increased temperatures, the floor sagged and the columns were pulled inward. Knuckle failure was found to occur mainly at the ends of the trusses and had little effect on the deflection of the floor system. Figure 6–11 shows that the diagonals at the core (right) end of the truss buckled and caused an increase in the floor system deflection, ultimately reaching approximately 42 in. Two possible failure modes were identified for the floor-truss section: sagging of the floor and loss of truss seat support.

Impact Damage

On damage to WTC1 pp20- 21

The 94 th floor was more severely damaged. The midsection of the left wing, laden with jet fuel, and the left engine cut through the building façade, severing 17 of the perimeter columns and heavily damaging four more. The pieces of the aircraft continued inward, severing and heavily damaging core columns. The insulation applied to the floor trusses above and the columns was scraped off by shrapnel-like aircraft debris and building wall fragments over a wedge almost 100 ft wide at the north face of the tower and 50 ft wide at the south end of the building core.

A 40 ft width of the 96 floor slab was broken 80 ft into the building. The insulation was knocked off nearly all the core columns and over a 40 ft width of floor trusses from the south end of the core to the south face of the tower.

On WTC1 p34

Dislodging of SFRM from structural members due to the aircraft impact, that enabled rapid heating of the unprotected structural steel;

On WTC2 78 flr p 40

Dislodging of SFRM from structural members due to the aircraft impact, that enabled rapid heating of the unprotected structural steel;

On WTC2 81 flr p 41

On the 81 st floor, the fuselage pulverized a section of the floor 40 ft wide that extended into the southeast corner of the core. The SFRM and gypsum fire protection on the full depth of the east side of the core and in the entire east side of the tenant space was stripped.

On impact p 105

The Investigation Team gained valuable knowledge from these component impact analyses, for example: • Moving at 500 mph, an engine broke any exterior column it hit. If the engine missed the floor slab, the majority of the engine core remained intact and had enough residual momentum to sever a core column upon direct impact. • The impact of the inner half of an empty wing significantly damaged exterior columns but did not result in their complete failure. Impact of the same wing section, but filled with fuel, did result in failure of the exterior columns.

On the accuracy of the impact model p 114

Two pieces of landing gear penetrated WTC 1 and landed to the south of the tower. The Case B prediction showed landing gear penetrating the building core, but stopping before reaching the south exterior wall. For WTC 2, a landing gear fragment and the starboard engine penetrated the building and landed to the south. The Case D prediction correctly showed the main landing gear emerging from the northeast corner of WTC 2. However, Case D showed that engine not quite penetrating the building. Minor modifications to the model (all within the uncertainty of the input data) would have resulted in the engine passing through the north exterior wall of the tower.

On damage to insulation, p 117

An intact ceiling tile system could have provided the floor trusses with approximately 10 min to 15 min of thermal protection 6.9.3 Damage to Thermal Insulation The dislodgement of thermal insulation from structural members could have occurred as a result of direct impact by debris and could have occurred by inertial forces due to vibration of structural members as a result of the aircraft impact. In interpreting the output of the aircraft impact simulations, NIST assumed that the debris impact dislodged insulation if the debris force was strong enough to break a gypsum board partition immediately in front of the structural component. Experiments at NIST confirmed that an array of 0.3 in. diameter pellets traveling at 350 mph stripped the insulation from steel bars like those used in the WTC trusses. Determining the adherence of SFRM outside the debris zones was more difficult. There was photographic evidence that some fraction of the SFRM was dislodged from perimeter columns not directly impacted by debris. NIST developed a simple model to estimate the range of accelerations that might dislodge the SFRM from the structural steel components. As the SFRM in the towers was being upgraded with BLAZESHIELD II (CAFCO II) in the 1990s, The Port Authority had measured the force required to pull the insulation from the steel. The model used these data as input to some basic physics equations. The resulting ranges of accelerations depended on the geometry of the coated steel component and the SFRM thickness, density and bond strength. For a flat surface (as on the surface of a column), the range was from 20g to 530g, where g is the gravitational acceleration. For an encased bar (such as used in the WTC trusses), the range was from 40g to 730g. NIST estimated accelerations from the aircraft impacts of approximately 100g. The analyses were not sufficient to establish justifiable, general criteria for a coherent pattern of vibration-induced dislodging. Thus, NIST made the conservative assumption that all other insulation remained adhered to the structural components.

Fire Modeling

Active Fire Protection: Active fire protection systems (i.e., sprinklers, standpipes/ hoses, fire alarms, and smoke management systems) should be enhanced through improvements to design, performance, reliability, and redundancy of such systems.

On Fireballs WTC1 p 24

Less than 15 percent of the jet fuel burned in the spray cloud inside the building. A roughly comparable amount was consumed in the fireballs outside the building. Thus, well over half of the jet fuel remained in the building, unburned in the initial fires.

On loading p 76

NIST estimated the fuel loading on these floors to have been about 4 lb/ft 2 (20 kg/m2), or about 60 tons per floor. This was somewhat lower than found in prior surveys of office spaces. The small number of interior walls, and thus the minimal amount of combustible interior finish, and the limited bookshelf space account for much of the differences.

On WTC fire in 1975 p 89

INFORMATION GAINED FROM OTHER WTC FIRES There had been numerous fires in the towers prior to September 11, 2001. From these, the Investigation Team learned what size fire WTC 1 and WTC 2 had withstood and how the tower occupants and the responders functioned in emergencies. While The Port Authority's records of prior fires were lost in the collapses, FDNY provided reports on 342 fires that had occurred between 1970 and 2001. Most of these fires were small, and occupants extinguished many of them before FDNY arrival. Fortyseven of these fires activated one to three sprinklers and/or required a standpipe hose for suppression. Only two of the fires required the evacuation of hundreds of people. There were no injuries or loss of life in any of these fires, and the interruptions to operations within the towers were local. A major fire occurred in WTC 1 on February 13, 1975, before the installation of the sprinkler system. A furniture fire started in an executive office in the north end of an 11 th floor office suite in the southeast corner of the building. The fire spread south and west along corridors and entered a file room. The fire flashed over, broke seven windows, and spread to adjacent offices north and south. The air conditioning system turned on, pulling smoke into the return air ducts. Telephone cables in the vertical shafts were ignited, destroying the fire-retarded wood paneling on the closet doors. The fire emerged on the 12 th and 13 th floors, but there was little nearby that was combustible. The fire also extended vertically from the 9th to the 19 th floors within the telephone closet. Eventually the fire was confined to 9,000 ft2 of one floor, about one-fourth of the total floor area. The trusses and columns in this area had been sprayed with CAFCO D insulation to a specified 1/2 in. thickness. Four trusses were slightly distorted, but the structure was not threatened.

On modeling floor fires, p 119

6.10.2 Modeling Approach The time frame of the Investigation and the above requirements led to the use of the Fire Dynamics Simulator (FDS). Under development at NIST since 1978, FDS was first publicly released in February 2000 and had been used worldwide on a wide variety of applications, ranging from sprinkler activation to residential and industrial fire reconstructions. However, it had never before been applied to spreading fires in a building with such large floor areas. Figure 6–30 shows how FDS represented the eight modeled floors (92 through 99) of the undamaged WTC 1. A similar rendition was prepared for floors 78 through 83 of WTC 2. The layout of each floor was developed from architectural drawings and from the information described in Section 5.8. There was a wide range of confidence in the accuracy of these floor plans, varying from high (for the floors occupied by Marsh & McLennan in WTC 1, for which recent and detailed plans were obtained) to low (for most of the space in WTC 2 occupied by Fuji Bank, for which floor plans were not available).

On the fuel load effect p 124

6.10.3 The Four Cases Four fire scenarios (Case A and Case B for WTC 1 and Case C and Case D for WTC 2) were superimposed on the four cases of aircraft-driven damage of the same names (Section 6.9). A number of preliminary simulations had been performed to gain insight into the factors having the most influence on the severity of the fires. The most influential was the mass of combustibles per unit of floor area (fuel load); second was the extent of core wall damage, which affected the air supply for the fires. The aforementioned workstation fire tests had also indicated that the damage condition of the furnishings also played a key role. The scenario variables and their values are shown in Table 6–6. Table 6–6. Values of WTC fire simulation variables. WTC 1 WTC 2 Variable Case A Case B Case C Case D Tenant fuel load a 20 kg/m2 (4 lb/ft2) 25 kg/m2 (5 lb/ft2) 20 kg/m2 (4 lb/ft2) 20 kg/m2 (5 lb/ft2) Distribution of disturbed combustibles Even Weighted toward the core Heavily concentrated in the northeast corner Moderately concentrated in the northeast corner Condition of combustibles Undamaged except in impact zone Displaced furniture rubblized All rubblized Undamaged except in impact zone Representation of impacted core walls b Fully removed Soffit remained Fully removed Soffit remained a. In addition, approximately 12,000 kg (27,000 lb) of solid combustibles from the aircraft were distributed along the debris path. b. In Cases A and C, the walls impacted by the debris field were fully removed. This enabled rapid venting of the upper layer into the core shafts and reduced the burning rate of combustibles in the tenant spaces. In Cases B and D, a more severe representation of the damage was to leave a 1.2 m soffit that would maintain a hot upper layer on each fire floor. This produced a fire of longer duration near the core columns and the attached floor membranes. FDS contained no algorithm for breaking windows from the heat of the fires. Thus, during each simulation, windows were removed at times when photographs indicated they were first missing. Damage to the ventilation shafts was derived from the aircraft impact simulations. For undamaged floors, all the openings to the core area were assumed to total 5 m 2 in area. 6.10.4 Characterization of the Fires

On the accuracy of spread p 126

The fire simulation results for Case A and Case B were similar, indicating only a modest sensitivity to the fuel load and the degree of aircraft-generated damage. This was because, in general, the size and movement of the fires in WTC 1 were limited by the supply of air from the exterior windows. Since the window breakage pattern was not changed in Case B, the additional and re-distributed combustibles within the building did not contribute to a larger fire. The added fuel did slow the spread slightly because the fires were sustained longer in any given location. Although there was generally reasonable agreement between the simulated and observed fire spread rates, there were instances where the fires burned too quickly and too near the windows. This resulted from an artifact of the model: the combustible vapors burned immediately upon mixing with the incoming oxygen. Simulations performed with doubled fuel loads slowed the fire spread well below the observed rates. Combined with the above results, this suggested that the estimated overall combustible load of 4 lb/ft 2 was reasonable.

On the predicted fires in WTC1, p 127

The predictions of maximum temperatures (e.g., red zones in Figure 6–37) were consistent with those in the three-workstation fire tests. The use of an "average" gas temperature was not a satisfactory means of assessing the thermal environment on floors this large and would also have led to large errors in the subsequent thermal and structural analyses. The heat transferred to the structural components was largely by means of thermal radiation, whose intensity is proportional to the fourth power of the gas temperature. At any given location, the duration of temperatures near 1,000 °C was about 15 min to 20 min. The rest of the time, the calculated temperatures were near 500 °C or below. To put this in perspective, the radiative intensity onto a truss surrounded by smoke-laden gases at 1,000 °C was approximately 7 times the value for gases at 500 °C.

On the modeling of WTC2, p 127

WTC 2 Simulating the fires in WTC 2 posed challenges in addition to those encountered in simulating the fires in WTC 1. The aircraft, hitting the tower to the east of center, splintered much of the furnishings on the east side of the building and plowed them toward the northeast corner. Neither the impact study nor the validation experiments performed at NIST could be completely relied upon to predict the final distribution, condition, and burning behavior of the demolished furnishings. In addition, only the layouts of the 78th and 80th floors were available to the Investigation; the other floors were only roughly described by former occupants. As a result of these unknowns, the uncertainty in these calculations was distinctly greater than in those for WTC 1. To help mitigate gross differences between the simulations and the observables, NIST made floor-specific adjustments, based on the results of preliminary computations. In particular, the fuel load and volatility on the 80 th floor were reduced, and the fuel load on the 81st and 82 nd floors was increased. In contrast with WTC 1, in WTC 2 there was less movement of the fires. The major burning occurred along the east side, with some spread to the north. There was no significant burning on the west side of the tower. Also unlike WTC 1, changing the combustible load in WTC 2 had a noticeable effect on the outcome of the simulations. Because so many windows on the impact floors in WTC 2 were broken out by the aircraft debris and the ensuing fireballs, there was an adequate supply of air for the fires. Thus, the burning rate of the fires was determined by the fuel supply. In the Case D simulation, the office furnishings and aircraft debris were spread out over a wider area, and the furnishings away from the impact area were undamaged. Both of these factors enabled a higher burning rate for the combustibles.

ON the heating of the structure by the FDS fire, p 139

Tables 6–8 and 6–9 summarize the regions of the floors in which the structural steel reached temperatures at which their yield strengths would have been significantly diminished. Instances of brief heating of one or two columns early in the fires were not included. Even in the vicinity of the fires, the columns and trusses for which the insulation was intact did not heat to temperatures where significant loss of strength occurred. Unlike the simulations of the aircraft impact and the fires, there was no evidence, photographic or other, for direct comparison with the FSI results. Table 6–8. **Regions in WTC 1 in which temperatures of structural steel exceeded 600 °C.** Trusses Perimeter Columns Core Columns Floor Number Case A Case B Case A Case B Case A Case B 93 – – – – – – 94 – – – – N, S NE, S 95 N N, S – – S NW, S 96 N N, S – S S W, S 97 N, S N, S – S N W, S 98 N N, S – – – – 99 – – – – – – Key: N, north; S, south; W, west; NE, northeast; NW, northwest. Table 6–9. **Regions in WTC 2 in which temperatures of structural steel exceeded 600 °C.** Trusses Perimeter Columns Core Columns Floor Number Case C Case D Case C Case D Case C Case D 79 – – – – – – 80 – – – – – – 81 NE NE NE NE – NE 82 E E E E E E 83 E E – E – E

On the fire duration predicted, p 144

Both the results of the multiple workstation experiments and the simulations of the WTC fires showed that the combustibles in a given location, if undisturbed by the aircraft impact, would have been almost fully burned out in about 20 min.

Insulation Saga

On insulation: p xlvi

NIST found no technical basis or test data on which the thermal protection of the steel was based. On September 11, 2001, the minimum specified thickness of the insulation was adequate to delay heating of the trusses; the amount of insulation dislodged by the aircraft impact, however, was sufficient to cause the structural steel to be heated to critical levels. • Based on four standard fire resistance tests that were conducted under a range of insulation and test conditions, NIST found the fire rating of the floor system to vary between 3/4 hour and 2 hours; in all cases, the floors continued to support the full design load without collapse for over 2 hours.

P55 on insulation

NIST was not able to find any evidence that there was a technical basis to relate SFRM thickness to a fire resistance rating, nor was there sufficient prior experience to establish such thickness requirements by analogy.

On insulation p 69

Floor Systems- At the time the WTC was designed, the ASTM E 119 test method had been used for nearly 50 years to determine the fire resistance of structural members and assemblies. However, The Port Authority confirmed to the Investigation Team that there was no record of fire endurance testing of the innovative assemblies representing the thermally protected floor system used in the towers. The floor assembly was not tested despite the fact that the Architect of Record and the Structural Engineer of Record stated that the fire rating of this novel floor system could not be determined without testing. Prior to construction, the Architect of Record had used information from (unidentified) manufacturers to recommend a 1 in. thickness of SFRM around the top and bottom chords of the trusses and a 2 in. thickness for the web members of the trusses. This was to achieve the fire endurance requirements for Class 1A construction (Section 5.3.3). In 1969, The Port Authority directed that a 1/2 in. thick coating of

CAFCO BLAZE-SHIELD Type D (CAFCO D), a mixture of cement and asbestos fibers, be used to insulate the floor trusses. This was to achieve a Class 1A rating, even though the preponderance of evidence suggests that the towers were chosen to be Class 1B, the minimum required by the NYC Building Code. NIST found no evidence of a technical basis for selection of the 1/2 in. thickness. This coating had been installed as high as the 38 th floor of WTC 1 when its use was discontinued due to recognition of adverse health effects from inhalation of asbestos fibers. The spraying then proceeded with CAFCO DC/F, a similar product in which the asbestos was replaced by a glassy mineral fiber and whose insulating value was reported by Underwriters Laboratories, Inc., to be slightly better than that of CAFCO D. On the lower floors, the CAFCO D was encapsulated with a sprayed material that provided a hard coat to mitigate the dispersion of asbestos fibers into the air. In 1994, The Port Authority measured the SFRM thickness on trusses on floors 23 and 24 of WTC 1. In all, average thicknesses were reported for 32 locations, and the overall average thickness was found to be 0.74 in. NIST performed a further evaluation of the SFRM thickness using photographs taken in the 1990s of floor trusses on (non-upgraded) floors 22, 23, and 27 of WTC 1 (Figure 5–5). By measuring dimensions on the photographs, NIST estimated the insulation thicknesses on the diagonal web members of trusses. (The thickness of chord member insulation could not be measured.) The average thickness and standard deviation of web members was 0.6 in. ± 0.3 in. on the main trusses, 0.4 in. ± 0.25 in. on the bridging trusses, and 0.4 in. ± 0.2 in. on the diagonal struts. These numbers indicated that there were areas where the coating thickness was less than the specified 0.5 in.

P 70

Chapter 5 Draft for Public Comment 70 NIST NCSTAR 1, WTC Investigation Note: Enhancement by NIST. Figure 5–5. Irregularity of coating thickness and gaps in coverage on SFRM–coated bridging trusses. In 1995, The Port Authority performed a study to establish requirements for retrofit of sprayed insulation to the floor trusses during major alterations when tenants vacated spaces in the towers. Based on design information for fire ratings of a similar, but not identical, composite floor truss system contained in the Fire Resistance Directory published by Underwriters Laboratories, Inc., the study concluded that a 1 1/2 in. thickness of sprayed mineral fiber material would provide a 2 hour fire rating, consistent with the Class 1B requirements. In 1999, the removal of existing SFRM and the application of new material to this thickness became Port Authority policy for full floors undergoing new construction and renovation. For tenant spaces in which only part of a floor was being modified, the SFRM needed only to be patched to 3/4 in. thickness or to match the 1 1/2 in. thickness, if it had previously been upgraded. In the years between 1995 and 2001, thermal protection was upgraded on 18 floors of WTC 1, including those on which the major fires occurred on September 11, 2001, and 13 floors of WTC 2 that did not include the fire floors. The Port Authority reported that the insulation used in the renovations was CAFCO BLAZE-SHIELD II. In July 2000, an engineering consultant to The Port Authority issued a report on the requirements of the fire resistance of the floor system of the towers. Based on calculations and risk assessment, the consultant concluded that the structural design had sufficient inherent fire performance to ensure that the fire condition was never the critical condition with respect to loading allowances. The report recommended that a 1.3 in. thickness be used for the floor trusses. In December 2000, another condition assessment concluded that the structural insulation in the towers had an adequate 1 hour rating, considering that all floors were now fitted with sprinklers. The report also noted the ongoing Port Authority program to upgrade the fire resistive material thickness to 1 1/2 in. in order to achieve a 2 hour fire rating. The Port Authority provided NIST with the records of measurements of SFRM thickness on upgraded floors in both towers. The average thickness and standard deviation on the main trusses was 2.5 in. ± 0.6 in. NIST analysis of several Port Authority photographs from the 1990s of the upgraded 31 st floor of WTC 1 indicated an average thickness and standard deviation on the main trusses of 1.7 in. ± 0.4 in. NIST found no statistically significant difference in the average thickness of the upgraded insulation in the two towers.

Perimeter Columns In 1966, the contractor responsible for insulating the perimeter columns proposed applying a 1 3/16 in. thick coating of CAFCO D to the three external faces (Figure 5-6) to achieve a 4 hour rating, which is a Class 1A rating requirement (1 hour more than Class 1B). NIST found evidence of a technical basis for this decision. In the construction drawings prepared by the exterior cladding contractor, the following SFRM thicknesses were specified: • 7/8 in. of vermiculite plaster on the interior face and 1 3/16 in. of CAFCO D on the other three faces. • 1/2 in. of vermiculite plaster on the interior surfaces of the spandrels and 1/2 in. of CAFCO D on the exterior surfaces. Figure 5-6. **Thermal insulation for perimeter columns.**

Vermiculite plaster had a higher thermal conductivity and thereby increased heat migration from the room air to the column steel and, thus, could keep the steel temperature at 70 °F when the temperature was 0 °F outside. In October 1969, The Port Authority provided the following instructions to the contractor applying the sprayed fire protection, in order to maintain the Class 1-A Fire Rating of the NYC Building Code: • 2 3/16 in. of CAFCO D for columns smaller than 14WF228 11 and 1 3/16 in. for columns equal to or greater than 14WF228. • 1/2 in. covering of CAFCO D for beams, spandrels and bar joists. NIST's review of available documents has not uncovered the reasons for selecting CAFCO fire resistive material or the technical basis for specifying 1/2 in. thickness of SFRM for the floor trusses. As with the trusses, CAFCO DC/F was applied to the perimeter columns above the 38 th floor of WTC 1 and all the perimeter columns in WTC 2. Core Columns and Beams Multiple approaches were used to insulate structural elements in the core: • Those core columns located in rentable and public spaces, closets, and mechanical shafts were enclosed in boxes of gypsum wallboard (and thus were inaccessible for inspection). The amount of the gypsum enclosure in contact with the column varied depending on the location of the column within the core. SFRM (CAFCO D and DC/F) was applied on those faces that were not protected by the gypsum enclosure. The thicknesses specified in the construction documents were 1 3/16 in. for the heavier columns and 2 3/16 in. for the lighter columns. • Columns located at the elevator shafts were protected using the same SFRM thicknesses. They were not enclosed and thus were accessible for routine inspections. Inspection of the columns within the elevator shaft spaces in 1993 indicated some loss of SFRM coverage. As a result, new insulation was applied to selected columns within the elevator shaft space. Information provided to NIST indicated that a different SFRM, Monokote Type 2-106, was used. Thickness measurements for columns and beams below the 45 th floor indicated average thicknesses of 0.82 in. and 0.97 in., respectively. Information from The Port Authority indicated that the minimum required thickness of the re-applied SFRM was 1/2 in. for the columns and 3/4 in. for the beams. NIST was unable to locate information from which to characterize the insulation of the core columns and beams that were not accessible. Except as noted above, once completed, the core was generally not inspected. NIST was not able to locate any post-collapse core beams or columns with sufficient insulation still attached to make pre-collapse thickness measurements.

On the selection of insulation, p 192

No technical basis was found for selecting the spray-applied fire resistive material (SFRM) used or its thickness for the large-span open-web floor trusses of the WTC towers. The assessment of the insulation thickness needed to meet the 2 hour fire rating requirement for the untested WTC floor system evolved over time: – In October 1969, The Port Authority directed the insulation contractor to apply 1/2 in. of insulation to the floor trusses. – In 1999, The Port Authority issued guidelines requiring that insulation be upgraded to 1 1/2 in. for full floors undergoing alterations. – Unrelated to the WTC buildings, an International Conference of Building Officials (ICBO) Evaluation Service report (ER-1244), re-issued June 1, 2001, using the same SFRM recommends a minimum thickness of 2 in. for "unrestrained steel joists" with "lightweight concrete" slab.

Recommendations

On major rec's p xlvii

The eight major groups of recommendations are: • Increased Structural Integrity: The standards for estimating the load effects of potential hazards (e.g., progressive collapse, wind) and the design of structural systems to mitigate the effects of those hazards should be improved to enhance structural integrity. • Enhanced Fire Resistance of Structures: The procedures and practices used to ensure the fire resistance of structures should be enhanced by improving the technical basis for construction classifications and fire resistance ratings, improving the technical basis for standard fire resistance testing methods, use of the "structural frame" approach to fire resistance ratings, and developing in-service performance requirements and conformance criteria for spray-applied fire resistive materials. • New Methods for Fire Resistance Design of Structures: The procedures and practices used in the fire resistance design of structures should be enhanced by requiring an objective that uncontrolled fires result in burnout without local or global collapse. Performance-based methods are an alternative to prescriptive design methods. This effort should include the development and evaluation of new fire resistive coating materials and technologies and evaluation of the fire performance of conventional and high-performance structural materials. ethecal and standards barriers to the introduction of new materials and technologies should be eliminated. • Improved ?????

Appendix B: November 2004 Comments

November 22, 2004

To: The National Construction Safety Team Advisory Committee
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From: James G. Quintiere

RE: NIST conclusions on the WTC collapse mechanism reported on October 19, 2004

The October surprise in the NIST investigation was the assertion that all of the core column insulation was knocked off by the airplane impacts. To a lesser extent, reliance on NYNJPA audit insulation data solidified the NIST assertion that the failure of the core columns, and not the trusses, were to blame for the collapses of the South and North towers. That audit information was reported by NIST to have the fire floors of the north tower with truss insulation thicknesses as an average of 2.5 inches up to 4 inches instead of the prescribed 1.5 inches.
NIST needs to produce demonstrable and clear substantive information to support this rationale for its conclusions. The core-damage theory was put forth by the Weidlinger group in the Silverstein civil suit, and I heard it expressed at a local ASME meeting over a year ago by a NIST staffer. Therefore, I think it is incumbent on NIST to explain when and how they came to this conclusion. This collapse mechanism conclusion has profound influence on the recommendations brought from this investigation. The airplane-caused column collapse theory yields significantly, and almost diametrically, opposed recommendations than the fire induced truss collapse mechanism.

NIST needs to validate its conclusion by addressing the following:

1. The NYNJPA North tower insulation data needs to be authenticated. There is a long saga on the insulation coverage of the truss assemblies, and it should not end with an audit report that contains data that are extraordinary. The claim that up to 4 inches of insulation was sprayed onto 1-inch diameter truss elements needs testimony, photographic corroboration, or other tangible evidence to establish the accuracy of this information.
2. It needs to be clearly demonstrated how the core column insulation was removed. This cannot simply be based on an assumption or an extrapolation from impact calculations. It is too important to the conclusions to have modeling as the sole basis. Sandia has been experimenting with airplane crashes into buildings. Have they been consulted for supporting information or assistance? NIST needs to live up to the Daubert-rulling in civil case law, and demonstrate a clear methodology for their conclusion that the insulation was removed.

<u>Finally, NIST needs to clarify inconsistencies</u> that appear in their public information to date. These inconsistencies and apparent weakness lead me to question their collapse theory, and place the collapse cause more on the lack of sufficient truss insulation.

1. NIST metallurgical analyses show no core columns from the fire floors reached temperatures above 250 C. It is claimed that this information is consistent with computer modeling. Moreover, I was pleased to see that after many inquiries for microscopic analysis of the steel debris, it was done and reported in the October briefing. The importance of forensic evidence to document the temperatures reached of the steel cannot be overlooked. First, its consistency with the modeling has little significance since the modeling cannot have that level of detailed accuracy precise fire effects around the core columns. Secondly, the core column theory requires that the columns got sufficiently hot, say 500 C, and tangible evidence from metallurgical analysis is crucial in supporting the NIST conclusion. Unfortunately, that evidence has not been found by NIST. Thirdly, as a consequence, this crucial lack of evidence must indict the selling of the WTC steel debris before an investigation could be launched. Will NIST speak to this as they now have future investigative authority?

2. NIST computations show that floor truss assemblies can fail at temperature measured in the UL tests. UL fire tests showed for ½ and ¾-inch insulation that steel truss temperatures exceeded 1300 F (704 C) in roughly 58 minutes and 62-76 minutes, respectively. They reached average temperatures of 1110 F (593 C) in 66 and 66-86 minutes, respectively. My own data with Isolatek indicate that individual web elements can reach 593 C in about 35 to 50 minutes, respectively for ½ and ¾ inches. NIST's model for a single WTC truss (which is more accurate than the impact computations), predicts a truss would fail at the column connections at these temperatures. The NIST model for a single truss and its connection shows that the truss fails at the interior column seat connection, and 'walks off' the seat. This occurs at 650 C. The web diagonals begin to buckle at 340 C, and the exterior columns bow inward at 560 C because the truss acts as a catenary. Other independent work done by Usmani et al, and Burgess et al., show similar results. If one floor falls on the floor below while both are heated by fire, can the impacted floor carry the load? Is this a plausible global collapse mechanism? To me, this means that truss failure is likely, at least in the South tower; and in the North if the PA audit data are wrong. Collapses of the floors were seen in both of the towers well up to 20 minutes before the buildings collapsed. This indicates the presence of the floor collapse mechanism.

   Incidently, the NIST scaling criterion used for the ½-scaling in the UL tests should be examined, as it is thermally not to scale. The shorter truss members will cause lower temperatures as the web transfers heat into the concrete floor.

3. NIST has relied on state-of-the-art computer models that are at the forefront of their technologies. However, these models have not been proven comprehensively for less complex incidents than the WTC. Will NIST continue to invest in these modeling technologies, or are they proven and ready for general use? If they are ready, will NIST advocate their use in design, or will NIST continue to perform research to improve them? If the latter is true, will NIST articulate the uncertain aspects of the modeling, and comment on how they bear on the investigation's conclusions?

4. NIST has used workstations fire experiments as a basis for their modeling. The stated fuel load is 4 lbs/ft^2 and this loading has been questioned, as it appears very low in the spectrum of office loadings. Because our students are conducting a scale model experiment of the 96th floor of the North tower, it forced us to examine this loading. While we could not pursue our information in depth, I can relate some major concerns. NIST experimental photographs of the office modules show little paper, and NIST has told me that the paper load was reported as light. I was told by a WTC inspector that the load was heavy, storage areas were overloaded and floors were continually cited for having paper stacked on the window sills; a furniture installer of the Marsh floors gave me information that showed extensive file cabinets surrounding the cubicles and these were not included in the NIST fire experiments – he, too, said that the Marsh office spaces were heavy in paper; an anonymous Marsh employee said that the Marsh company were paper "hogs", and a family member said it was heavy as well. The fuel loading is crucial to the duration and the temperatures of the fires. A light fuel load in the modeling will lead to low temperatures and this would affect the overall results.

It is imperative that NIST get the cause of the WTC tower collapses correct. The legacy of its victims bears on future fire safety. The protection of buildings in fire and terrorists attacks will be impacted by these conclusions, so they need to be right. The Advisory Panel plays a clear role to sign off on these conclusions. I know of others that feel the NIST conclusions need, in the least, clarity, and in the main, more support. However, we are few in number, and it falls on you to insure the public that they got it right.

<u>Recommendations</u> that should come from this study are submitted in no priority order as suggestions for your consideration:

1. Experimental studies to establish temperatures and fire duration characteristic of modern facilities including office large plan spaces, places assembly, and underground structures should be undertaken to validate models and establish design methods. The current correlations are incomplete in terms of fuel type and building type.

2. The standard time-temperature structural fire tests should be examined in light of computational methods. Data for the tests yielding temperature and deflection should be integrated with computations to extrapolate to actual assemblies used in practice.
3. Sensor technologies integrated with alarm monitoring for building performance should be integrated into the emergency response network for assessing the nature of the hazard.
4. Forensic techniques and standards should be established to assess failure information from structural debris. The elimination of the steel structure from the WTC site should be fully addressed, and its consequences fully stated.
5. Fire and disaster planning should include full and proper analyses for safe egress and effective response. Responders and building planners need to have the benefit of analyses that quantitatively address these facets. Real time modeling of the fire effects based on sensor information are possible and should be integrated into special building designs and response actions.
6. Novel techniques need to be investigated to rescue people and to fight high-rise fires.
7. Current codes weaknesses, in light the WTC collapses, need to be fully addressed. Issues of lightweight construction designs that are vulnerable to catastrophic collapse of a structure need particular attention.
8. A nationally supported infrastructure is needed to insure that objective scientific input is placed into the code consensus process to bring fire safety to a proper level of engineering analyses. The current code process is lacking in scientific underpinning, and the WTC disaster should stand for change in this direction, especially if the scientific community cannot render a clear and decisive verdict.

October Review:

Review of NIST WTC Investigation
Addressing Tasks 3, 5 and 6.

J. G. Quintiere
September 11, 2004

Modified October 17, 2004

The following constitutes the NIST projects designed to reach the objective of the investigation.

NIST Projects: Federal building and fire safety investigation of the WTC disaster

Project No./Technical Area /Project Purpose

1. Analysis of Building and Fire Codes and Practices
    a. Document and analyze the code provisions, procedures, and practices used in the design, construction, operation, and maintenance of the structural, passive fire protection, and emergency access and evacuation systems of the WTC 1, 2, and 7.
2. Baseline Structural Performance and Aircraft Impact Damage Analysis
    a. Analyze the baseline performance of WTC 1 and 2 under design, service, and abnormal loads, and aircraft impact damage on the structural, fire protection, and egress systems.
3. Mechanical and Metallurgical Analysis of Structural Steel
    a. Determine and analyze the mechanical and metallurgical properties
4. Investigation of Active Fire-Protection Systems
    a. Investigate the performance of the active fire protection systems in WTC 1, 2, and 7 and their role in fire control, emergency response, and fate of occupants and responders.
5. Reconstruction of Thermal and Tenability Environment
    a. Reconstruct the time-evolving temperature, thermal environment, and smoke movement in WTC 1, 2, and 7 for use in evaluating the structural performance of the buildings and behavior and fate of occupants and responders.
6. Structural Fire Response and Collapse Analysis
    a. Analyze the response of the WTC towers to fires with and without aircraft damage, the response of WTC 7 in fires, the performance of open-web steel joists,

and determine the most probable structural collapse sequence for WTC 1, 2, and 7.

7. Occupant Behavior, Egress, and Emergency Communications
    a. Analyze the behavior and fate of occupants and responders, both those who survived and those who did not, and the performance of the evacuation system.
8. Fire Service Technologies and Guidelines
    a. Building on work done by the Fire Department of New York and McKinsey & Company, document what happened during the response by the fire services to the WTC attacks until the collapse of WTC 7;
    b. identify issues that need to be addressed in changes to practice, standards, and codes;
    c. identify alternative practices and/or technologies that may address these issues; and
    d. identify research and development needs that advance the safety of the fire service in responding to massive fires in tall buildings.

The NIST investigation objectives are:

1. To determine (a) why and how the WTC 1 and WTC 2 collapsed following the initial impact of the aircraft, and (b) why and how the 47-story WTC 7 collapsed.

2. To determine why the loss of life and injuries were so low or so high depending on location, including technical aspects of fire protection, occupant behavior, evacuation, and emergency response.

3. To determine the procedures and practices which were used in the design, construction, operation, and maintenance of the WTC buildings.

4. To identify, as specifically as possible, areas in national building and fire codes, standards, and practices that warrant revision.

Among the **specific questions that NIST is investigating** within the above four objectives are the following:

- How and why did WTC 1 stand nearly twice as long as WTC 2 before collapsing (103 min versus 56 min), though they were hit by virtually identical aircraft?
- What factors related to normal building and fire safety considerations not unique to the terrorist attacks of September 11, 2001, if any, could have delayed or prevented the collapse of the WTC towers?
- Would the undamaged WTC towers have remained standing in a normal major building fire?
- What factors related to normal building and fire safety considerations, if any, could have saved additional WTC occupant lives or could have minimized the loss of life among the ranks of first responders on September 11, 2001?
- How well did the procedures and practices used in the design, construction, operation, and maintenance of the WTC buildings conform to accepted national practices, standards, and codes?

I will address Tasks 3, 5 and 6 in the format indicated below:

<u>Issue</u> for the project
<u>Approach</u> taken by NIST
<u>Questions</u> on the Approach
<u>Comments</u> on ability to address objectives

3. Mechanical and Metallurgical Analysis of Structural Steel

Objective: Determine and analyze the mechanical and metallurgical properties

Issue

NIST has established the mechanical and thermal properties of the steel used in the WTC, and generally has found no remarkable departures from the literature for steel. However, an important aspect of this fire and large fires in general is the temperature reached by the fire, and that achieved by the steel.

NIST approach

In the December 2003 Public Update it states that part of this task objective is "estimating the maximum temperature reached by available steel" (p.8). In the May 2003 (p. 33) and June 2004 Vol. 1, p. 87), it appears that this objective is being done by examining paint degradation at 250 and 750 C.

Questions

A common forensic technique for determining the temperature reached by steel in a fire is to microscopically examine the grain size. It has been said that very precise determinations can be made if compared to an unheated similar steel sample. Why has NIST not used this method?

Comments

The importance of knowing the temperature achieved by the steel on the fire floors is crucial to establishing the cause of the buildings collapse. This is like a thermometer in the building, so its significance cannot be overlooked. The temperature of the fire and the steel are important in determining the time and the nature of the collapse of the buildings. NIST is using computational methods to predict these temperatures. It is incumbent on NIST to use all methods for ascertaining the steel temperatures to achieve confirmation of its predictions.

Also, NIST has steel samples salvaged from the dumpsite, and has said those samples were adequate. NYC made a unilateral decision to remove and sell the steel before the NIST investigation began. What is the NIST recommendation on how to preserve evidence in future investigations in order to render complete structural and thermal analysis to the debris samples? Was the steel prematurely discarded in the WTC before adequate analysis could occur?

5. Reconstruction of Thermal and Tenability Environment

Objective: Reconstruct the time-evolving temperature, thermal environment, and smoke movement in WTC 1, 2, and 7 for use in evaluating the structural performance of the buildings and behavior and fate of occupants and responders.

Issue

The accuracy of the computer modeling predictions for the fire environment need to be assessed, and their consistency with literature data for fully developed fires and with the factual evidence of the WTC fires needs addressing. A computation of this magnitude is beyond the state of the art for fire modeling, and although NIST and the investigators should be commended for their efforts at pushing the state of the art, they must not solely rely on computer-driven computations for estimating the fire temperatures. They have other sources from which to also draw information on the state of the fire: They include: conducted fire tests, correlations for fully developed fires in the literature, data on window breakage and the fire progress, and people reaction to the fire heat and smoke from potential interviews. Consistency must be assessed between the various sources of information and from alternative, albeit, simpler computational methods.

NIST Approach

Information about the fire can come from several sources. NIST has extensively examined and compiled the fire behavior and its effect on the building through the correlation of various photographic evidence. This task has been done with excellence it appears, and should offer valuable information. Another source of fire could come from the collection of data from people. This appears to have lagged and it is not clear that anything of value in a timely manner will be reported on the fire and damage effects observed directly by people and ascertained through interviews. In all of the fire predictions NIST has chosen to use its Fire Dynamics Simulator (FDS) as the sole computational tool. In order to evaluate its accuracy, experiments have been conducted on small features of the WTC office occupancies in order to calibrate and assess the accuracy of the fire predictions. Hence, both the modeling and the experimental data offer information on the WTC fires. As with other aspects of the investigation, NIST appears to be weighting the computational approach as their primary result, especially since that result must be supplied to the structural modelers in order to make their prediction of the building's ability to carry its load.

NIST has approached the validation effort by conducting two series of tests. The first series consisted of a spray fuel fire in a compartment containing structural members. The second involved a larger compartment containing three workstations that NIST decided were representative of the WTC offices. That fuel load is roughly 4 lb/ft^2 (psf) (or about 20 kg/m^2 and 50 MJ/ m^2), June 2004 Vol. 1, p xxxvii, Vol. 5, J-37.

Series 1 consisted of the following (June 2004 Vol. 5, J-2):

> The test compartment consisted of a steel stud frame lined with calcium silicate board. The internal dimensions of the compartment were 3 m high, 7 m deep, and 4 m wide. There were four openings in the west wall through which air entered the room; they totaled 1.75 m 2 (10.8 ft^2) in area and were located 1 m (3.3 ft) above the floor. There were four openings in the east wall through which heat and combustion products were emitted; they also totaled 1.75 m^2 (10.8 ft^2) in area and were located 2 m above the floor. In each of the six tests, the four test subjects were a bar, two trusses, and a thin-walled tubular column. Depending on the test, these specimens were either left unprotected or were coated with spray-applied fire protective insulation material, Blaze Shield DC/F. The fibrous insulation was applied by an experienced applicator who took considerable care to apply an even coating of the specified thickness. As such, the insulated test subjects represent a best case in terms of thickness and uniformity. The fires consisted of liquid hydrocarbon fuels sprayed by a two-nozzle spray burner onto a 1 m × 2 m (3.3 ft × 6.6 ft) pan. The fuels were (a) heptanes and (b) a mixture of nominally 60 percent (by mass) heptanes with 40 percent toluene. The latter fuel produced a significantly sootier flame.

Six tests were done. The instrumentation for the tests comprised up to 352 channels of data.

Series 2 consisted of 3 workstations in a large room (June 2004, Vol. 5, J-27):

> Six experiments were designed to assess the accuracy with which FDS predicts the fire spread, heat release rate, and thermal environment in a compartment burning multiple workstations in a configuration characteristic of that found in the WTC buildings. In each of these experiments, sets of three workstations were burned in a large compartment (about 11 m x 7 m x 3.4 m high). The challenges to the model included varying the location of the ignition burner (and thus the fire ventilation), adding jet fuel and/or noncombustible material occluding a fraction of the workstations' surfaces, and "rubblizing" the workstations.
>
> It should be noted that the workstation fuel load was "suggested by personnel from a company that supplied office furnishings to the occupants of WTC 1. Information on the distribution of papers and other office items was provided by a frequent visitor to these offices". (p J-12)

NIST performed some additional computations based on FDS. They have early on reported on the smoke dynamics from the building (Rehm et al., IAFSS 2002), and recently on the fireball dynamics (Baum, Comb. Inst., 2004). These are considered somewhat ancillary to the prediction of the fire conditions on the floors that bear directly on the heating of the structure and the effect of the fire on the ultimate collapse. However, the work by Prasad and Baum (Comb. Inst. 2004) on linking the predictions of FDS for the fire with the heating of core columns under different core damage scenarios is very significant. It is the closure of the fire and the structure modeling that is critical to answering the issues pertaining to collapse. McGrattan has simulated the fires on a floor based on the workstation fuel load. That loading was indicated at about 4 pounds per square ft of office space (psf). McGrattan indicates the fire at this low fuel loading burn in an under-ventilated state as "oxygen consumed drives fires to the windows" (p. J-44). In addition, these full-scale WTC computer simulations are reported to for about 20 minutes in a region and then move on with an entire floor burning out in about 1 hour (Fact Sheet June 2004 pp. 2, 3).

Also it was indicated that these simulated fire burn at an average temperature over the floor at about 600 C.

<u>Questions</u>

It is well known that FDS results depend on the grid size and its scaling to the fire conditions. The experiments done by NIST may well serve the credibility and accuracy of using FDS with a grid size of 40 cm, but enough comparison has not been shown between the computations and the experiments. Only about 4 or 5 plots have been presented for comparison in the reports, and they show very good prediction for the fire gas temperatures and heat release rate. Some of NIST's own funded work (Ierardi and Barnett, 2003) have shown that the accuracy of predicting a single fire plume from a 30 cm burner give drastic variations in temperatures with the fire plume for grids of 1.5 to 15 cm. Temperatures within 20 per cent of the experiment results required grids of 1.5 to 5 cm. So it is incumbent on NIST to address this accuracy question completely. They have done 13 experiments with over 300 measuring stations in each test. In the least, NIST needs to demonstrate the ability of FDS to compute all aspects that FDS has in common with these measurements.

The issue of accuracy for computer models is a serious matter when they are to be used as general engineering tools. The literature is filled with data and correlations for fully develop fires. NIST should at least demonstrate how its approach using FDS compares to these other empirical approaches in the literature. Japan uses one of these empirical approaches as a design method in regulations, and the SFPE has just completed a guide on the prediction of fire conditions for structural considerations. It has been said that the full WTC floor simulation agree with the phenomenon observed by (I. Thomas et al.) in which the fire moves about the compartment seeking air. Can FDS predict the data of Thomas? These questions are broader that the effort that has gone into the WTC simulation, and therefore it would be important for NIST to examine FDS in light of its validation needs. Moreover, FDS is using a charring model to compute the burning rate and flame spread on the workstations, and NIST should state the accuracy of using FDS for the prediction of flame spread on charring materials. Boeing would not take the use of CFD models in its aircraft design lightly, and neither should those assessing fire behavior, especially from NIST.

The fuel load selected in the representative experiments and the modeling raises some questions. NIST is using roughly 4 psf, and a floor burns for an average of about 1 hour (Key Findings of NIST's June 2004 Progress Report...). This selection of loading is critical to establishing the burning time, crucial to predicting the impact of fire on the structure. The literature (Robertson and Gross, ASTM STP 464, 1970) suggests an average office load of 18.4 psf, ranging from 7 to 43 psf according to surveys. Why is the WTC representative office so low? This needs examining and supportive data.

The FDS simulations indicate a one-hour burning period for a floor at 600 C. This may be due to the light fuel, but appears inconsistent with the under-ventilated burning achieved in the simulation. Also the actual fires appear to have burned longer with WTC burning until collapse at 103 minutes. Finally, the average temperature of 600 C is about coincident with critical failure temperature associated with steel structures, and would never allow the steel to reach this temperature.

In an investigation where information comes in different forms, the final analysis must show that the information pieces are consistent. NIST has observational information, hopefully people information, experimental test information, and the FDS simulations. These must be shown to be consistent.

Ultimately FDS results must be linked to a structural model. Prasad and Baum (C.I. 2004) have attempted this for the heating of the core columns. They show that simplifications need to be made in representing the FDS temperature spatial distributions in order to better interface with the structural heating model. Their approach has demonstrated the needed closure of the fire and structural heating. However, they have not considered the vulnerable floor assembly in their calculations. This will need to be added to fully assess the role of the fire on the complete structure. NIST has not made clear how the fire and structural computations will come together, particularly since the structural modeling is being done under contract. We would like to see NIST speak to the accuracy and issues related to the modeling of the fire and structure together.

Since NIST has test data on the heating of insulated structural members in their fire tests, some comparisons, at least, need to be presented for these simpler fire scenarios.

Can NIST successfully modeling the 1975 WTC fire (June 2004, Vol. 4, G-1) that did extensive damage to a floor? This fire prompted the use of sprinklers, and local structural damage occurred. Since the damage and extent of the fire was known, it could be a useful benchmark for NIST to compare their simulations.

Comments

The fire computations are perhaps the most important determination since its heating impact and its duration determine the ultimate temperature of the protected steel. The heat transfer by conduction into the insulation and the steel is trivial by comparison. Also when it realized that failure in furnace testing of structures is often based on steel temperature, and temperature strongly affects the strength of steel, e.g. the modulus of elasticity is reduced by 50 % when steel attains about 600 C. Since the modulus is directly related to the critical load to cause buckling, the buckling of elements in compression can occur more easily at elevated temperatures. The ability of the fire modeling to relate to the structural heating model is very import step in this investigation. NIST should make this step as transparent as possible in order to judge its conclusions. FDS will yield a spatial and time varying temperature throughout a floor. Its accuracy needs to be supported at this level of sophistication. Alternative estimates on the level of temperature and its duration might need to be couched in simpler forms for the best structural analysis to be produced. It might serve just as well to specify uniform temperature in a range. The duration will depend on the fuel load, and it has been pointed out that the NIST selected load is very low compared to office load surveys. Some variation of uncertainty must be considered here.

Finally, it appears almost foolish to have received $16 million for the investigation and to not have conducted a test more representative of a WTC floor. A quarter of a floor could have been tested for fire and the heating of the structure. It would only involve a plan space at 100 x 100 feet. This could have settled many issues. Especially when it is realized that no experimental results exist for compartments with small ratios of height to their lateral dimension as 1/20 in the

WTC. The smallest has been ¼ in the well known CIB studies, and those results should be examined by NIST for their applicability. However, the interaction of air from the perimeter and fuel within the compartment need to be examined under these conditions by an experiment, to at least see if FDS is qualitatively correct. Moreover, it is known that in large fire plumes that smoke can trap radiation and drive the core fire temperatures to 1300 C and more. This can happen at fires of 30 ft in diameter, so the question must be raised if this might apply to the WTC with lateral floor dimensions of 200 ft.

6. Structural Fire Response and Collapse Analysis

Objective: Analyze the response of the WTC towers to fires with and without aircraft damage, the response of WTC 7 in fires, the performance of open-web steel joists, and determine the most probable structural collapse sequence for WTC 1, 2, and 7.

Issue

The principal issue here is to examine the NIST working hypothesis in conjunction with its collection of findings and to assess their consistency. The working hypothesis is found in June 2004 Vol. 6, Q-3.

> The working hypothesis addresses the following chronological sequence of major events; specific load redistribution paths and damage scenarios are currently under analysis:
>
> 1. Aircraft impact damage to perimeter columns with redistribution of column loads to adjacent perimeter columns and to the core columns via the hat truss;
> 2. After breaching the building's exterior, the aircraft continued to penetrate into the buildings, damaging core columns with redistribution of column loads to other intact core and perimeter columns via the hat truss and floor systems;
> 3. The subsequent fires, influenced by post-impact condition of the fireproofing, further weakened columns and floor systems (including those that had been damaged by aircraft impact), triggering additional local failures that ultimately led to column instability;

4. Initiation and horizontal progression of column instability ensued when redistributing loads could not be accommodated any further. The collapses then ensued.

NIST Approach

NIST and its contractors are using computational analyses to compute the impact damage by the aircrafts, the performance of a single floor truss under temperature elevation, the evaluation of a portion of the floor assembly in the ASTM E 119 test, and the history of the insulation applied in the WTC, especially to the floor assembly.

2. Impact computations: These computations are portrayed in figures on pp 78-79 of June 2004, Vol. 1, and they show an engine impacting and shredding a floor and then buckling a core column.

NIST reports further (June 2004, Vol. 1, p 81):

• A 500 mph engine impact against an exterior wall panel results in a penetration of the exterior wall and failure of impacted exterior columns. If the engine does not impact a floor slab, the majority of the engine core will remain intact through the exterior wall penetration with a reduction in velocity of about 10 percent and 20 percent. The residual

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

velocity and mass of the engine after penetration of the exterior wall is sufficient to fail a core column in a direct impact condition. Interaction with additional interior building contents prior to impact or a misaligned impact against the core column could change this result.

Also an analysis of the stability of the towers, assuming no damage to the core, gives the number of floors that need to be removed to cause global failure (June 2004, Vol. 1, p.81):

The following presents some preliminary findings obtained from the preliminary stability analyses under service live loads and subject to the assumptions and the limitations of these models (see Appendix D): Linear stability analysis was used to examine the stability of the undamaged WTC 1 under service loads through increased un-braced column lengths (floor removal). The tower was stable when two floors were removed. Two core columns buckled when three floors were removed, but the tower maintained its overall stability. The tower also maintained its stability when four columns buckled with four floors removed. The analysis suggested that global instability of the tower occurred when five floors were removed from the model. Assuming that all columns at the region of the removed floors reached a temperature of 600 °C (reduced modulus of elasticity), the analysis indicates that removal of four floors would induce global instability.

3. Single truss analysis: A model of a single truss and its connection shows that the truss fails at the interior column seat connection, and 'walks off' the seat. This occurs at 650 C. The web diagonals begin to buckle at 340 C, and the exterior columns bow inward at 560 C because the truss begins to act as a catenary. (June 2004, Vol. 1 p. 120).

4. E 119 tests: Standard fire tests were conducted at UL. Two were done at a 35 ft span representing the short span in the WTC towers. These had ¾ in. thickness of insulation applied. A third test was conducted with public viewing with ½ in. insulation, and at a span of 17 ft. In that test the truss was scaled –down so that it was half its depth. The failure criterion used was primarily structural integrity for the most part. The third test was conducted *restrained* and obtained a 2 hour restrained rating meaning it did not structurally collapse, and it obtained a 1 hour unrestrained rating which results from exceeding a critical temperature of the steel.

5. Insulations history: NIST has traced documents and recommendations related to the thickness of insulation, particularly on the floor joist assembly. They have found and stated the following:
   a. The truss specified thickness was 0.5 in., but as applied was 0.6 +/- 0.3 inch.

b. The upgraded truss insulation was 1.5 inches (based on UL G805, May 2003, p. 78), but was later measured in application as 1.7 +/- 0.4 inches based on photographic analysis, but was reported in audit documents over 1997 to 1999 as 2.5 +/0.6 inches, with thickness as high as 4 inches (June 2004, Vol. 4, I 15-18).

c. A model code recommended 2 inches for 2 hours in a 2001 assessment of a similar truss (June 2004).

d. A report by Burro-Happold recommended in 2001 that the upgraded insulation could be dropped to 0.5 inches based on an ambient value of the conductivity used in a calculation, but settled on a recommendation of 1.3 inches. (May 2003, p. 82)

Questions

Column impact: It is very important to determine an accurate estimate of the core column damage. In view of the variability of the impact computer codes, what does NIST consider is their accuracy? It was reported by the NY Times that the Weidlinger computations indicated that the South tower would fall solely upon impact of the aircraft. It is know that calculations were made in 1966 that indicated only local damage would occur. Why is there so much variability in these computations? In addition, the NIST reported results indicate that an engine needs to directly strike a core without loss of momentum for the column to fail. This would suggest very limited core column damage is possible as might be inferred from the NIST computational graphic shown above. Can an engine possibly hit a core column without hitting anything on the floor occupancy and structure? That does not seem possible, so how can an engine damage a core column? Perhaps I am missing something. Why is NIST then considering in its "working hypothesis" that considerable core damage is likely? Moreover, it is known that landing gear and at least one engine was found in the surrounding streets suggesting a flight path through the building. Can NIST use information on the location of the engines to assess the likelihood of core column damage?

Temperature importance for floor failure: The single truss analysis done by NIST and the work done both Usmani et al, and Burgess et al., indicate that the truss deflections occur at temperatures ranging from roughly 400 to 600 C. During these deflections, the truss can cause failure to its connections, or to column instability. It would seem that temperature is a key feature in causing failure. How does NIST relate its work to those cited above in the literature? If one floor falls on the floor below while both are heated by fire, can the impacted floor carry the load? Will this be a mode of global collapse? NIST considers the number of floors to be removed before the columns would become unstable, but would not the loss of 2 or 3-floors cause the failure before this instability? Is a critical temperature a good measure of structural failure as it might appear from the element computations, and the implication of the loss in strength at elevated temperatures?

Role of E119: Ratings have been achieved at UL for the E-119 test. Will NIST be analyzing these results to see how they would apply to the WTC? If the temperatures reached by the steel in these tests is sufficient to cause failures in the WTC computations, but the structure did not fall in the E 119 test, how will NIST reconcile these differences? NIST scaled the depth of the truss to ½ full-scale in its 17 ft E 119 test. This was done for stress purposes, but the heat transfer along the web into the concrete deck is now changed. Since temperature is a criterion for failure of the test in some modes of testing, the temperature of particularly the full-scale 35 ft. truss should be examined. Moreover, as UL G805 was used for justifying the 1.5-inch insulation thickness, why would the recent tests give such different results? Also UL N 826 might have been more appropriate, and gives 2 1/16 inches. So what is the meaning of the E 119 test and how should it be used in this WTC analysis?

Reconciliation of insulation thicknesses: As seen by the various E 119 results for the Cafco insulation, and the varied specifications and recommendations on the WTC truss insulation, it is incumbent on NIST give some rationality to these variations. Since the amount of insulation is so crucial to the outcome of finding the cause, NIST needs to be very sure about how much insulation was actually in place. The latest information from PANYNJ indicates that the upgrade in WTC 1 could have been as much as 4 inches over the 1.5 specification, when field workers were having difficulties in application, and that was the main reason for the Burro-Happold report. A 4-inch radius on a 1 inch steel rod would give a 9-inch diameter cylinder – a very big result. How much confidence does NIST have on these large amounts? Do they have photographic evidence as in the previous smaller amounts? Would not a hearing on the insulation thickness issues serve NIST well in documenting the facts and rationality of these variations? If so much variation occurred for the WTC, how does this relate to the protection in other buildings?

Comments

It appears that NIST has to answer some very focused questions with clarity and accuracy.

1. How many core columns were removed and why?
2. How much insulation was in place during the fire?
3. What are the critical temperatures needed for failure?
4. Could the fire cause these temperatures?

The global collapse mechanism of the buildings must be made as clear as possible. A vague answer expressed by the current NIST working hypothesis is not sufficient. NIST has expended a lot of good individual effort, and it has done some very good fact finding and analyses. Now all of that has to be put together, and it seems contractors (who we have not heard from) play a significant role. NIST needs to harness those individual efforts and expertise in a balanced evaluation. Reliance solely on complex computer models should not be the sole basis of the answers. If the core of the answers are really revealed and understood, NIST should be able to explain them in simple fundamental physics, and not shroud them in computer graphics. This was the purpose of the investigation, and this project task is critical.

Appendix C:

Analysis of the Fuel Load Calculations for the 96th Floor of the WTC North Tower

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April 2005
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Abstract

An impartial examination into the combustible fuel load for the 96th floor of the North World Trade tower is described in this paper.

Introduction

The dimensions used for analysis of the WTC North tower are as follows, the overall building dimensions are 207.2' x 207.2' = 42,932 ft^2 (3988.5 m^2), building core dimensions are 87' x 137' =11,919 ft^2 (1107.3 m^2), and the area that office equipment sits on is therefore 31,013 ft^2 (2881.2 m^2), while FEMA reports that area for office furniture is 30,930 ft^2 (2,873.5 m^2) [1].

Typical structural live loads used in design or analysis for offices are 50 psf (pounds per square foot) (244.35 kg/m^2), and for lobbies, 100 psf (488.7 kg/m^2).

The paperweight found in the Marsh & Mc Lennan office is significant because it directly impacts the fire size/duration, which in turn, affects results obtained for performance of structural members.

UMCP considerations and examination:

- The cabinets used by NIST contained two reams of packed paper, which is not consistent with the files that I weighed. The significance is that the tighter the packed paper is, the less air can get in to feed the fire whereas, typical files are not uniform in size or spacing and leave room for air to supply the fire.
- The following are graphical representations of the difference between the paper weight not included (NIST) and the total weight inclusion (UMCP):

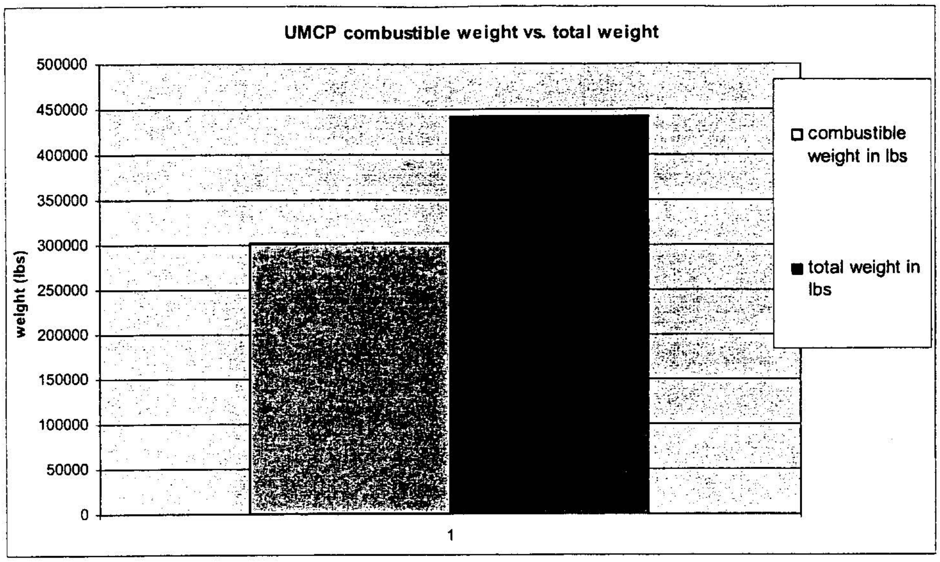

Figure 1. UMCP estimate of how the total workstation weight is distributed.

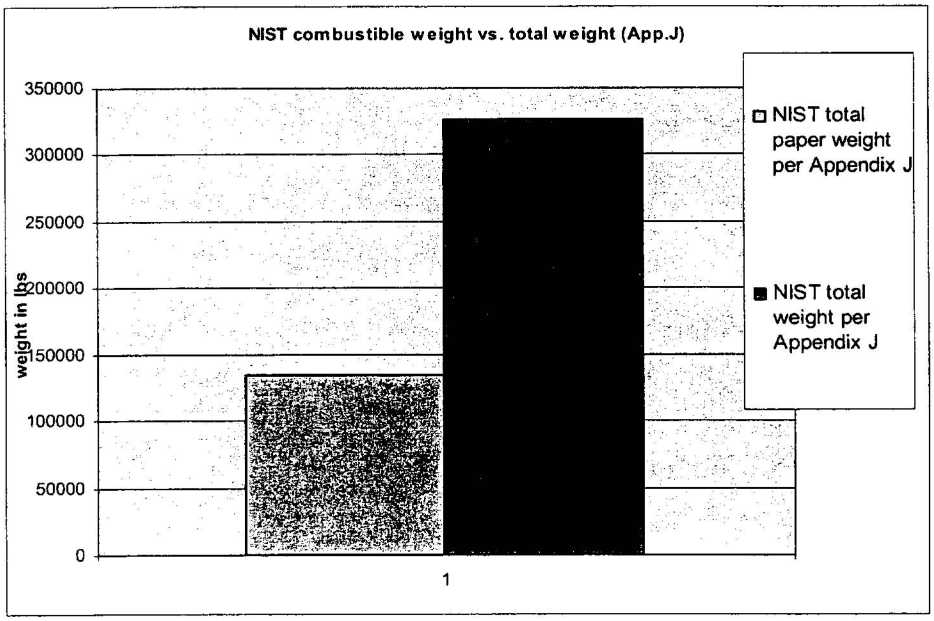

Figure 2. NIST estimate of how the total workstation weight is distributed.

Summary of results from NIST

- The book case, which was 48" high (1.22m), was stuffed with 10 boxes containing 13 reams of copier paper (260 lb ~ 118 kg).
- Total workstation weight considered to be 1600 pounds (726 kg) and the amount of combustible material contained in that workstation was estimated as 660 pounds (300 kg) by NIST. Based on the information obtained in these simulations, McGrattan then passed the FDS results onto others who analyzed the temperature of the steel and concrete [2].
- NIST used a per desk weight rather than obtaining combustibles for the entire floor and attributing that to their experiments. However, in the impact zone, there are two conference rooms (~1,590 lbs (721 kg) of combustible materials), 8 sets of four drawer lateral files (48 cabinets=192 drawers~13,824 lbs (6270.5 kg) (of paper that was likely dislodged by the impact) and the paper storage area (~28,000 lbs (12,701 kg) of paper & paper/office products) that directly contribute to the initial fire started by the jet fuel.

Information obtained from FEMA

- Estimated combustible fuel load as 8 psf.
- Additionally, the report acknowledges that typical office loading is 50 psf, per Load Resistance Factored Design published by American Society of Civil Engineers. (50*31013=1,550,650 lbs (7,577,988 kg) live load- i.e. combustible and non-combustible materials)

Methodology used for this examination

- The assumptions made for this project are as follows:
  1. That the symbols had not changed for the Knoll furniture between those used in 1997 and those used today.
  2. Veneer panels close in weight to panels used by NIST.
  3. Used FEMA building and core dimensions and assumed NIST did the same.
  4. Based on NIST drawing, I counted 204 workstations but according to plans from Dr. Quintiere, there were 210 workstations. I used 210 workstations.

5. Estimated that there were 20 units of five shelf storage files by the stairwell area. Each unit was determined to have dimensions 63" high x 36" wide (1.6 m x 0.9 m) and it was assumed that items were stored on top of the shelving units.
6. One Calibre cabinet held 15 lbs ~ 6.8 kg (of contents and one 3-drawer pedestal contained one paper file with 17" (0.4 m) of file storage (24 lbs ~ 10.9 kg of paper weight).
7. Southeast corner of building plan did not photocopy well therefore assumptions were made consistent with other corners of the 96th floor layout.

- The approximations made are as follows:
  1. The weights for chair models that were not found in the symbol library (perhaps not manufactured by Knoll), like "CH6", were estimated based on other known chair weights.
  2. Wall panels and workstation layout based on information provided by NIST [3]: (5) 4'panels-36"wide, (1) 5' panel-36"wide and (5) 4' panels-24"wide. In SI units: (5) 1.2 m panels- 0.91 m wide, (1) 1.5 m panel- 0.91 m wide, and (5) 1.2 m panels-0.61 m. The two foot panel weights were estimated using 10.55 lbs (4.8 kg) per foot of height.
  3. Based on files weighed in the ENFP office, an average file weight was obtained of 2 lbs/inch using standard paper size, type 20 wt.
  4. Only desks that could be positively identified as having a computer were given 'credit' for one (i.e. 165 computers for 210 workstations)
  5. Trapezoidal conference room table weight was estimated based on locating it once in AutoCAD, noting that there were several sizes, and then not being able to locate the table again.
  6. Knoll representative did not want to be quoted on specific amounts of combustible material in furniture.
  7. A request of the Manufacturer must be made in order for the privacy panels to be chemically treated to meet ASTM E-84 class "A" flame spread rating.

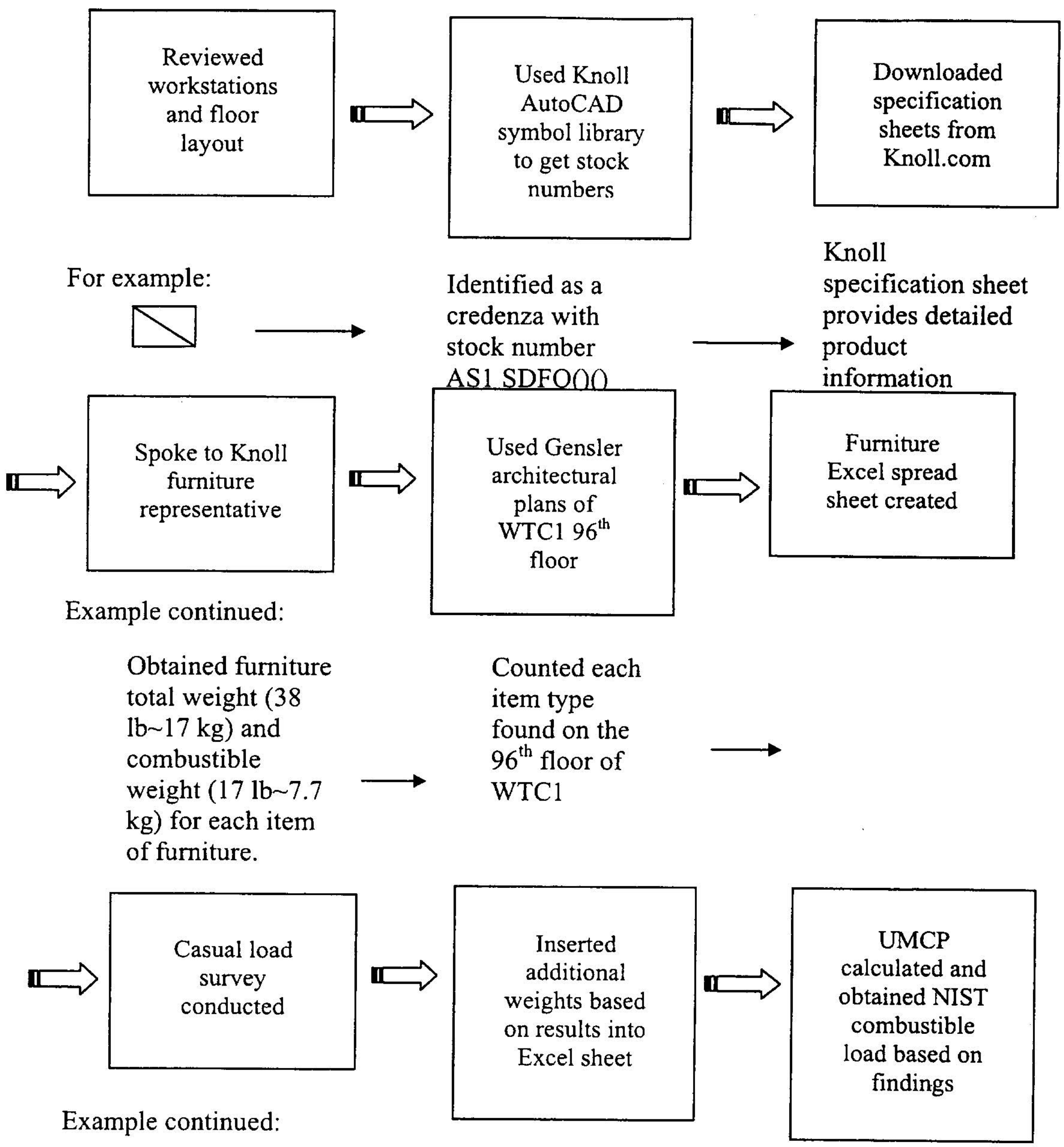

Figure 3. This flow chart demonstrates the methodology used to obtain furniture identifications.

Comparisons

The following comparison table is provided to sum-up the previously mentioned information and to clearly layout the three groups being compared.

Table 1.

	COMPARISON				
TOTAL WORKSTATION WT.	Average	High	Low		
description	UMCP			NIST	FEMA
Number of desks	211			204	
Total psf(*combined contents)	14.3				
Combustibles only desk wt	179441	1429	341		
Paper weight (lbs)	302062			134640	
Empty furniture weight (lb)	265162			191760	
Full furniture weight (lb)	441868			326400	248103
30% paper weight (lb)	90619				
Building area (ft^2)	42932				42932
Core area (ft^2)	11919			11745	11919
Area that furniture sits on	30930			31000	31013
Common file cabinets (lb):					
noncombustible	37626			0	
combustible	36,437			0	
combust. stored on top	255				
Total	74318				
Conf. rms/areas & pantries(lb)	7117			0	
***Combustible Material (psf)**	**10**			4 psf	8psf (39 kg/m^2)
SINGLE WORKSTATION WT.					
Combustible wrkstn weight	862	1443	341	660 lbs	
Total				1600lbs	
Wrkstn. weighted average (lb)	862				
Added Combustibles:					
workstation paper (lb)		370	6	160	
additional (lb)		30	0	0	
File cabinets:					
contents (lb)		424	124	40	
top (lb)		6	3	0	
workstation foot print	8'x8' (2.41 m * 2.41 m)			8'x8'	
paper NIST left out	71,844 lbs				

Comparison of fuel load between UMCP and NIST:

Table 2.

	NIST	UMCP
Total floor weight (combustible + noncombustible)	1600 lbs x 204 stations=326,400lb	210 stations x 1433 lb =301,012 lb
Total Combustibles Weight	134,640 lb/30930 ft^2= 4.3 lb/ft^2 combustibles only	301,012 lb/30930 ft^2 = 9.7 ~ 10 psf
*Paper weight for floor distributed per station	60,242 lb/204 wrkstns = 295 lbs.	176,706 lb /210wrkstns = 841 lbs.

*paper weights for NIST and UMCP are different because UMCP included common lateral files and paper storage whereas NIST did not.

**The reason for 1141.4 lbs of combustible per station is based on the accessible fuel per NIST. However, this is too low an estimate due to the fact that common files were not taken into account, nor conference rooms etc...

***This is the weighted average of the workstations.

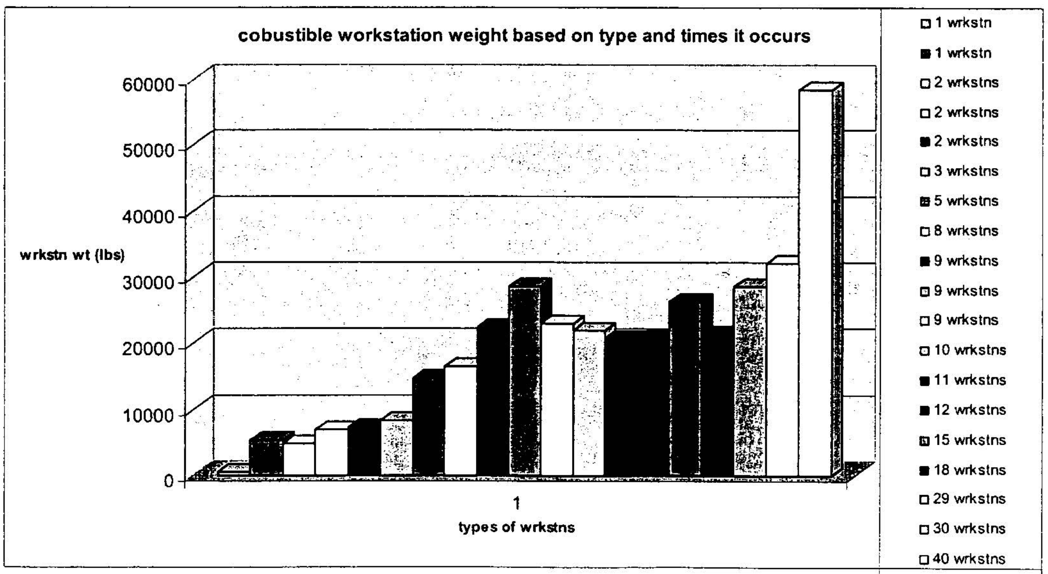

Figure 4. UMCP chart showing weight of workstation type plotted against the number of times the workstation type occurs on the 96th floor.

Recommendation

Use the NIST data for the temperature of steel then make a plot versus temperature of the outer steel insulation. The purpose of this plot is to help linearly estimate, based on corrected fuel load/fire size, the possible range of steel temperatures. Then, using something like SAFIR or lumped heat capacitance or maybe T. T. Lie's work, there would be a reference check as to the validity of the results.

From the above described course of action, a strong enough case can be made, which may prove to NIST that a re-examination of their original fuel load estimates is worthwhile.

References

1. McAllister, T., et al. FEMA WTC report "Chapter 2" page 2-1
2. McGrattan, K. "Simulation of the fires in WTC 1 and 2" BFRL, NIST, US Department of Commerce, October 19, 2004, slide 2.
3. NIST Preliminary WTC report 2004, Appendix J.

Other References not specifically cited:

4. NIST AND THE WORLD TRADE CENTER website "Status of Data Collection Efforts"
5. McGrattan, K. "Simulation of the fires in WTC 1 and 2" October 19, 2004. BFRL, NIST, US Department of Commerce.
6. McGrattan, K. "Simulation of the fires in WTC 1 and 2" October 19, 2004. BFRL, NIST, US Department of Commerce.
7. Knoll furniture catalog www.knoll.com/products

	wish to send confirmation of combustible weights via email).
H5 & I5	Combustible weight in lbs and kgs respectively
J3-J4	Weight of paper in one item is an estimate of the amount of paper to be found in/on a particular piece of furniture. This information was obtained by casual load observations and calculations of file cabinet weight and desk weight where applicable. These are conservative estimates!
J5 & K5	Paper weight in lbs and kgs respectively
J9	Calibre cabinet was not given a paper weight of 15 lbs each but rather an estimate for clothing, note pads and other office items. The 15 lbs were put under weight of paper for ease of reference.
L2-L4	Total weight of paper for all items means that the weight of paper for one furniture item has been multiplied by the number of items on the floor.
L5 & M5	Total paper weight in lbs and kgs respectively
N2-N4	Combined weight for one full item means combustible and noncombustible weight of one full item. This column provides the total weight of one piece of a particular furniture type; self weight plus paper weight.
N5 & O5	Total furniture weight in lbs and kgs respectively
P2-P4	Total weight of combustible material for full item, this column provides the combustible weight of the furniture plus the added paper weight for one piece of a particular furniture type.
P5 & Q5	Combustible material weight in lbs and kgs respectively
R2-R4	Total combustible weight is the weight of combustible material times (x's) number of items. This means that the total combustible weight (P column) was multiplied by the number of times that piece of furniture was found on the 96^{th} floor (G column).
R5 & S5	weight in lbs and kgs respectively
T2-T4	Total combustible and noncombustible weight provides the furniture self weight plus the added paper weight.
T5 & U5	Total weight (combustible + noncombustible) for 96^{th} floor in lbs and kgs respectively

V3-V4	Total weight of the furniture only (both combustible and non-combustible furniture weight. Note, there is no added paper weight here)
V5 & W5	Furniture weight, only, for 96th floor in lbs and kgs respectively
B6-B25	Items that may be located in a workstation, there were different designs; these office items were found among the workstations on the 96th floor.
B27-B30	Common files refer to the lateral files that were either at the end of a workstation grouping or in a common area. (previously left out by NIST)
B32-B39	These are the different types of conference chairs found on the 96th floor.
B41-B45	These are the different types of conference tables found on the 96th floor.
B47-B51	These are the different types of common items found on the 96th floor.
B53-B61	These are the different common/shared rooms located on the 96th floor.
B63	Despite there being different sizes and weights of paper used, the estimate was based on Boise 20weight, 500 sheet 5 lb reams.
Notes:	
C7	The three file credenza was only included by NIST for the brand mane workstation. Appendix J shows that there was not a credenza for the generic workstation but rather a third two drawer file cabinet. If this was to account for the lack of a credenza then the combustible furniture weights were significantly different. (Credenza combustible weight of 17 lbs vs. all metal for the two drawer lateral file). If this was an attempt to account for the files at the end of workstation groupings then they should have been placed outside the workstation and the credenza would have been negated.
C9	The Calibre cabinet was not shown in any of the Appendix J photos but was present on the 96th floor, per Gensler, in the amount of 62 units with a **combustible** weight estimate of 175 lbs each!
Row 66	Provides 'sum' of columns
NIST	
A1	For ease of identification when printed I inserted column and row details.
A68	Row and designations for ease of reference.

B70	Heading to show that the following data is from NIST, Appendix J of preliminary report.
B71	Classification for the description of where the furniture item may typically found on the 96th floor from Appendix J.
C70	Item type refers to the physical description of an individual item found on the 96th floor as obtained from Gensler Architectural plans and Appendix J of the NIST preliminary WTC report.
D70	Stock identification numbers were obtained from comparing the Gensler Architectural plans to the AutoCAD symbol library obtained from www.Knoll.com
E69	Total weight of each item refers to the weight of one piece of furniture as it is, complete and unpacked. These weights were obtained from a Knoll Sales person.
E70	Weight of furniture in pounds (lbs)
F70	Weight of furniture in kilograms (kgs)
G68-G69	Number of items refers to the number of items found on the 96th floor of WTC 1. This information was obtained from Gensler Architectural plans except that the number of desks came from the FDS office graphic in Appendix J.
H68-H69	The weight of combustible material for empty furniture item refers to the amount of material for a single, unused piece of furniture (obtained from Knoll sales person who was referring to either a binder or computer when we spoke but did not wish to send confirmation of combustible weights via email).
H70 & I70	Combustible weight in lbs and kgs respectively
J68-J69	Weight of paper in one item is an estimate of the amount of paper to be found in/on a particular piece of furniture. This information was obtained by casual load observations and calculations of file cabinet weight and desk weight where applicable. These are conservative estimates!
J70 & K70	Paper weight in lbs and kgs respectively
L68-L69	Total weight of paper for all items means that the weight of paper for one furniture item has been multiplied by the number of items on the floor.
L70 & M70	Total paper weight in lbs and kgs respectively

N68-N69	Combustible and noncombustible weight of one full item, this column provides the total weight on one piece of a particular furniture type, self weight plus paper weight.
N70 & O70	Total furniture weight in lbs and kgs respectively
P68-P69	Total weight of combustible material for full item, this column provides the combustible weight of the furniture plus the added paper weight for one piece of a particular furniture type.
P70 & Q70	Combustible material weight in lbs and kgs respectively
R68-R69	Weight of combustible material times (x's) number of items means that the total combustible weight (P column) was multiplied by the number of times that piece of furniture was found on the 96th floor (G column).
R70 & S70	weight in lbs and kgs respectively
T68-T69	Total combustible and noncombustible weight provides the furniture self weight plus the added paper weight.
T70 & U70	Total furniture weight for 96th floor in lbs and kgs respectively
B71-B84	Items that may be located in a workstation, there were different designs; these office items were found among the workstations on the 96th floor.
Notes:	
C73	The three file credenza was only included by NIST for the brand mane workstation. Appendix J shows that there was not a credenza for the generic workstation but rather a third two drawer file cabinet. If this was to account for the lack of a credenza then the combustible furniture weights were significantly different. (Credenza combustible weight of 17 lbs vs. all metal for the two drawer lateral file). If this was an attempt to account for the files at the end of workstation groupings then they should have been placed outside the workstation and the credenza would have been negated.
C72	The Calibre cabinet was not shown in any of the Appendix J photos but was present on the 96th floor, per Gensler, in the amount of 62 units with a **combustible** weight estimate of 175 lbs each!

Row 86	Provides 'sum' of columns
R86	Is the amount of combustible weight calculated by UMCP using NIST data however, it does not include carpet tiles and ceiling tiles. That contributes to the discrepancy UMCP(106,705 lbs) vs. NIST (660 lbs * 204 desks-134,640 lbs)
T86	Is the amount of total weight calculated by UMCP using NIST data however, it does not include carpet tiles and ceiling tiles. That contributes to the discrepancy UMCP(247,098 lbs) vs. NIST (1600 lbs * 204 desks-326,400 lbs)

Table 2. For Excel sheet 'wrkstn wts'

Column designation	Description of how the value was obtained and/or what it means/relevance
A1	Row and column designations for ease of reference.
B2	Heading to show that the following data is calculated from information obtained by Quintiere & Stewart of UMCP.
C2	WTC1 96th floor ('wrkstn wts') to let reader know which printed sheet they are viewing.
E3, H3, P2, Z2 & AM2	These are sub category designations.
G2	All weights on this sheet are in pounds.
B4	Description refers to designation of the employee who was originally assigned to that desk location on the 96th floor.
C4	Station identification is the number assigned on the architectural plans for a particular desk location.
D4	Telephone extension for a particular workstation
E4	Staff refers to the COMBUSTIBLE weight of one staff chair.
F4	Visitor refers to the combustible weight on staff chairs that can be attributed to that workstation.
G4	Conference refers to the conference area/room chairs that correspond to the

	designated location.
H4	J-shape refers to the style of knoll table that can be found at that workstation location; combustible weight is provided and does not include mounting or legs.
I4	Is the paper weight most likely to be found on the J-shape table and is an estimate of the amount of paper to be found on furniture. This information was obtained by casual load observations and calculations of file cabinet weight and desk weight where applicable. These are conservative estimates!
J4	½ round table refers to the style of knoll table that can be found at that workstation location; combustible weight is provided and does not include mounting or legs.
K4	Is the paper weight most likely to be found on the ½ round table and is an estimate of the amount of paper to be found on furniture. This information was obtained by casual load observations and calculations of file cabinet weight and desk weight where applicable. These are conservative estimates!
L3-L4	Teardrop or circular table refers to the style of knoll table that can be found at that workstation location; only combustible weight is provided and does not include mounting or legs.
M2-M4	Is the paper weight most likely to be found on the teardrop or circular tables and is an estimate of the amount of paper to be found on furniture. These two tables were grouped together because they have nearly identical weight as provided by Knoll customer service representative. This information was obtained by casual load observations and calculations of file cabinet weight and desk weight where applicable. These are conservative estimates!
N4	This is the boat shaped conference table that is located in the following conference rooms: NE, NW, SE, & SW
O3-O4	Is the paper weight most likely to be found on the boat shaped table and is an estimate of the amount of paper to be found on this furniture. This information was obtained by casual load observations and calculations of file cabinet weight and desk weight where applicable. These are conservative estimates!
P2-P4	Wall Panels: 4 foot high and two feet wide privacy panels used at each desk. The weight of 3 panels*14 lbs = 42 lbs.
Q3-Q4	Is the paper weight most likely to be found on the three privacy panels and is an

	estimate of the amount of paper to be found on these pieces of furniture. One privacy panel was observed to have 0.15 lbs of paper attached to it which is ~ 15 sheets of standard paper. This information was obtained by casual load observations and calculations of privacy panel decorations, calendars and other items.
R3-R4	Wall Panels: 4 foot high and three feet wide privacy panels used at each desk. The weight of 3 panels*24 lbs = 72 lbs.
S3-S4	Is the paper weight most likely to be found on the three privacy panels and is an estimate of the amount of paper to be found on these pieces of furniture. One privacy panel was observed to have 0.15 lbs of paper attached to it which is ~ 15 sheets of standard paper. This information was obtained by casual load observations and calculations of privacy panel decorations, calendars and other items.
T3-T4	Wall Panels: 5 foot high and three feet wide privacy panels used at each desk. The weight of 1 panel*35 lbs = 35 lbs.
U3-U4	Is the paper weight most likely to be found on the three privacy panels and is an estimate of the amount of paper to be found on these pieces of furniture. One privacy panel was observed to have 0.15 lbs of paper attached to it which is ~ 15 sheets of standard paper. This information was obtained by casual load observations and calculations of privacy panel decorations, calendars and other items.
V3-V4	Overhead cabinet refers to the double door cabinet that attaches to the five foot high privacy panel. The estimated combustible weight provided.
W2-W4	Paper weight for the overhead cabinet obtained from NIST Appendix J
X3-X4	Combustible weight of the Calibre cabinet (not included by NIST at all)
Y3-Y4	Additional weight is the added combustible weight for this furniture item.
Z2-Z4	Credenza 3-drawer is another furniture item that NIST did not include but rather per appendix J, equated cabinet fronts, presumably to justify negation
AA2-AA4	Paper weight for the one horizontal file drawer, one slender drawer and another miscellaneous storage drawer. Again, this information was obtained by weighing the file contents of two different ENFP horizontal drawers and adding additional

	weight for note pads etc…
AB2-AB4	Lateral file two-drawers refer to the all metal personal lateral files found at each workstation.
AC2-AC4	This is the paper weight contained in the lateral files, capacity is 150 lbs per drawer but I used 100 lbs per drawer based on the file contents of the horizontal drawer survey mentioned previously.
AD3-AD4	Common files used a wood counter-top
AE2-AE4	Paper weight likely to be found on wood counter-tops
AF3-AF4	This is the standard desk, Morrison, as obtained the Gensler architectural drawings and AutoCAD symbol library. This is the combustible weight of the desk only and does not include the mounting or table legs.
AG3-AG4	Paper weight that is likely to be found on this desk, it is a conservative estimate, and the information was obtained from a casual load survey.
AH2-AH4	Supplementary worktable (square or one rounded edge), these are added to the Morrison desk set-up based upon the workstation design, as obtained from Gensler architectural drawings. This is the combustible weight of the desk only and does not include the mounting or table legs
AI3-AI4	Paper weight that is likely to be found on this desk, it is a conservative estimate, and the information was obtained from a casual load survey.
AJ3-AJ	Computer monitor at workstation. Not all workstations appear to have a computer and there is '?' for any location that I was unsure about.
AK2-AK4	Computer hard drive at workstation.
AL3-AL4	Additional – unable to id means that there was something at that workstation that unidentifiable from Gensler architectural drawings.
AM2-AM4	Some workstations have additional chairs attributed to them; that is all this column is referencing.
AN2-AN4	Lateral files: 3 drawer metal file cabinets that is part of the common files.
AO2-AO4	Lateral files: 4 drawer metal file cabinets that is part of the common files.
AP2-AP4	Common files used a wood counter-top
AQ2-AQ4	Paper weight likely to be found on wood counter-tops

AR2-AR4	Corresponding panels refer to the panels that line some parts of the file cabinet groups.
AS2-AS4	Comment on which workstation design repeats; designated by employee.
AT2-AT4	Total times it occurs refers to the number of times that workstation design can be found on the 96th floor.
AU2-AU4	Combustible weight for an individual workstation type
AV2-AV4	Combustible sum of workstation weight per type
AW2-AW4	Combustible weight of file cabinets that NIST left out from their experimental burns.
AX2-AX4	Noncombustible weight of file cabinets that NIST left out from their experimental burns, 3 drawer cabinet.
AY2-AY4	Noncombustible weight of file cabinets that NIST left out from their experimental burns, 4 drawer cabinet.
AZ2-AZ4	Noncombustible weight of open metal shelving units that NIST left out from their experimental burns, 6 metal shelves.
BA	Sum of the combustible weight of other rooms on the 96th floors.

A.8 Excel Sheets
(attached)